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RESIDENTIAL LIT FIREPLACE DETECTION AND DENSITY MEASUREMENT USING AIRBORNE MULTI-SPECTRAL SENSORS

By

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Both locally (San Francisco Bay Area) and nationally, evidence is mounting that particulate matter poses a serious health risk. Locally, concentrations of 10 micron particles are highest on cold nights, during the months of December and January. Analysis of the composition of these 10 micron particles suggests that a large percentage is wood smoke. Currently, there are no adequate ways to estimate the number of lit fireplaces on a given night. NASA Ames Research Center, the Naval Postgraduate School and San Francisco Bay Area Air Quality Management District performed a joint research project to determine the feasibility of using thermal imagery to detect lit fireplaces.

This thesis addresses the use of an airborne multi-spectral remote sensing system to detect lit fireplaces. The focus will be on the remote sensing equipment used for fireplace detection, the development of the test plan, airborne data collection, ground truthing and data analysis.

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RESIDENTIAL LIT FIREPLACE DETECTION AND DENSITY MEASUREMENT USING AIRBORNE MULT-SPECTRAL SENSORS

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ABSTRACT

Both locally (San Francisco Bay Area) and nationally, evidence is mounting that particulate matter poses a serious health risk. Locally, concentrations of 10 micron particles are highest on cold nights, during the months of December and January. Analysis of the composition of these 10 micron particles suggests that a large percentage is wood smoke. Currently, there are no adequate ways to estimate the number of lit fireplaces on a given night. NASA Ames Research Center, the Naval Postgraduate School and San Francisco Bay Area Air Quality Management District performed a joint research project to determine the feasibility of using thermal imagery to detect lit fireplaces.

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I. INTRODUCTION

Both locally and nationally, mounting evidence suggests that airborne particulate matter poses a significant health risk. Studies show that wood smoke is a major source of the particulate matter that may cause health risks [Ref. 1].

Currently, in the local area, the San Francisco Bay Area Air Quality Management District (BAAQMD) is looking for a way to efficiently and accurately determine the approximate number and spatial distribution of lit fireplaces and wood stoves, over a large area, on any given night. This information would be used to help BAAQMD develop an inventory of emissions from residential wood burning and, ultimately, to evaluate the contribution of residential wood burning to ambient levels of particulate matter and carbon monoxide in the San Francisco Bay area.

BAAQMD has plans to apply grid-based models to study particulate matter transport and formation and attempt to determine sources. In using grid-based models, BAAQMD first divides an area into a number of cells or grids and then runs a meteorological model to predict air currents in each cell. Then they determine the source of particulate pollution and use the meteorological information to estimate where the pollutants may accumulate. To use grid-based models, BAAQMD must be able to spatially locate known particulate sources, such as residential woodburning. Currently, BAAQMD's knowledge of the extent and dispersion of residential woodburning in the Bay Area is inadequate to apply to their grid-based models.

Remote sensing offers a way to determine level of activity and spatial distribution.

In order to determine the feasibility using thermal imagery to detect lit fireplaces, BAAQMD air quality modelers, National Aeronautics and Space Administration (NASA) Ames Research Center engineers and the Naval Postgraduate School initiated a joint research project. Their approach was to use an airborne thermal imagery system to measure the level of thermal energy emitted from objects on the ground. NASA Ames was a leader in this type of research, and it had one of the few airborne platforms with a thermal infrared scanner readily available for use in the San Francisco Bay area.

A proposal submitted by the C-130 Mission Manager, Medium Altitude Missions Branch, NASA Ames, resulted in funding for this joint project being provided through the Fiscal Year 1996 Ames Director's Discretionary Fund [Ref. 2]. If successful, this initial research could provide a new technique to measure the relative contributions of specific sources to airborne pollution. This may lead to additional projects with other state and local agencies because of the increased concern over wood smoke, its contribution to airborne particulate matter and everyday requirements for communities to inventory pollution sources.

The purpose of this thesis is to determine whether or not an airborne mult-spectral scanner can detect lit fireplaces. If lit fireplaces can be easily differentiated from other thermal heat sources on homes, data processing software may then be programmed to automatically determine fireplace density over a given area, providing near real-time data to scientists.

The background chapter of this thesis will give the history of BAAQMD and examine airborne pollution sources, their health effects, measurement of airborne particulate matter as related to state and federal particulate standards.

Chapter III contains a brief introduction to remote sensing, which includes an explanation of the physical properties of the environment that are applied when conducting remote sensing. This chapter also provides a description of the thermal infrared imaging system used for this research project.

The next major section, Chapter IV, addresses the development of the test plan that was used to conduct the experiment. Critical segments of the test plan include the objectives and scope of the experiment, ground tests, ground survey and flight tests.

Chapter V will present the data collected throughout different phases of the experiment. Included in this section are the methods and procedures required to reduce and process the information obtained during various portions of the test.

The final section is a summary of findings and contains conclusions drawn from the results of the experiment and recommendations for follow-on research.

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II. BACKGROUND

A BAY AREA AIR QUALITY MANAGEMENT DISTRICT

The Bay Area Air Quality Management District (BAAQMD) was founded in 1955. It was created to help reduce air pollution from industrial operations, open burning, motor vehicles and residential sources in the area surrounding the San Francisco Bay. In addition to the local San Francisco area, BAAQMD's jurisdiction, hereafter referred to as the Bay Area, extends to Marin, Sonoma and Napa counties to the north; Solano, Contra Costa and Alameda counties to the east; and San Mateo and Santa Clara counties to the south. [Ref. 3]

Through a 1-800 telephone number, BAAQMD provides daily air quality conditions, forecasts, status of burn days and written material on how the general population can help clean the air. Additionally, they provide advisories such as the summertime "Spare The Air" and the winter "Don't Light Tonight." The "Spare the Air" advisories are primarily ozone related and urge residents to cut back on activities such as driving and using aerosol products, oil based paints, and varnishes. The "Don't Light Tonight" requests are issued to encourage residents not to light their fireplaces and woodstoves. Evidence of BAAQMD's success is the measured improvement of air quality in the Bay Area during the past 25 years. [Ref. 3]

B. POLLUTION SOURCE

Two quantities of interest to BAAQMD are the levels of carbon monoxide and particulate matter in the air. Carbon monoxide is a product of incomplete combustion and is emitted when all types of fuels, from gasoline to firewood, are burned. In the Bay Area, motor

vehicle use causes over 70 percent of carbon monoxide; residential woodsmoke is another major contributor [Ref. 3]. Carbon monoxide levels are measured in parts per million (ppm), with the highest concentrations occurring between November and February.

The other quantity of concern to BAAQMD is the PM_{10} level. PM_{10} is defined as airborne particulate matter (PM) smaller than 10 microns in diameter. By comparison, the diameter of human hair varies from 30 to 130 microns. Road and land dust, automobile exhaust, and wood smoke are the largest sources of particulate matter in PM_{10} [Ref. 3]. A 1992 study conducted by BAAQMD on PM_{10} levels in the Bay Area found that PM_{10} followed several distinct patterns [Ref. 1]. The first of these patterns was that PM_{10} had a very strong seasonal component. The highest levels occurred in the winter months, with December being the worst, followed by January and November. A characteristic of these months was cold winter inversions that trapped pollutants close to the ground. Inversions are common occurrences in California valleys. As night falls, air at ground level cools. In addition, cold air also slides down the valley walls, pooling on the valley floors. With little or no wind, warm air acts as a "lid" over the valley, trapping woodsmoke and other pollutants close to the ground. The second pattern, although not as pronounced, was diurnal. The highest levels of PM_{10} tended to occur in the late evening and during the morning rush hour. Elevated levels of PM_{10} in the late evening did not coincide with the evening rush hour, but were attributed to use of residential woodstoves and fireplaces. [Ref. 3]

Initial research conducted on inventories of PM_{10} emissions estimated that road dust constituted approximately 50%, construction

and domestic burning added 10% each, industrial and commercial processes added another 5% each, and the remainder came from a variety of sources. The BAAQMD study cited above, conducted during the winter of 1991-92, found that wood smoke was the largest source of PM_{10}, at about 40%, followed by road dust, auto exhaust and ammonium nitrate, each contributing about 15-20%. [Ref. 1]

C. HEALTH EFFECTS

The BAAQMD study cited numerous other studies that have implicated particulates as a source health problems. These studies found that there was increased mortality on days with elevated particulate levels, even at concentrations normally found in the Bay Area. Some of these studies also noted a correlation between the high levels of particulate and higher age-adjusted mortality rates for metropolitan areas. [Ref. 1]

BAAQMD also cited several studies that found associations between increased hospital admissions and emergency room visits and daily particulate levels. Although not as compelling, evidence exists for a correlation between elevated particulate levels and chronic diseases such as bronchitis and cancer. [Ref. 1]

PM_{10} is a primary concern because the natural filters of the human nose and throat cannot stop small these particles. PM_{10} particles penetrate deeply into the human body with fine particles, less than 2.5 microns, being carried into the avioli, the part of the lung where blood oxygen transfer occurs.

D. MEASUREMENT OF POLLUTION LEVELS

BAAQMD uses the federal Pollutant Standards Index (PSI), to provide Bay Area residents with daily air quality measurements. The PSI translates pollution levels measured at the BAAQMD's monitoring stations, located throughout the Bay Area, into a number. The PSI readings are divided into three ranges, which correspond to air quality descriptions of good, moderate, or unhealthful. Table 2-1 provides daily PSI readings and their corresponding carbon monoxide and PM_{10} levels.

Pollution levels	PSI reading	Carbon Monoxide (ppm)	PM_{10} ($\mu g/m^3$)
Good	0-50	0-4.5	0-50
Moderate	51-100	4.6-9.0	51-150
Unhealthful	101-199	9.1-14.0	151-349

Table 2-1. Bay Area Pollution Levels. From Ref. [2].

E. STATE AND FEDERAL PARTICULATE STANDARDS

Original state and federal particulate standards were based on the total amount of suspended particles up to 30 microns in size. However, current government standards are now based on the number of particles smaller than 10 microns (PM_{10}). The new standards are in response to evidence showing that only these smaller particles penetrate beyond the nose and throat. Presently, the federal government and the state of California each have two sets of standards in effect for concentrations of PM_{10}: an annual standard to protect against chronic effects and a 24-hour standard to protect against acute effects. [Ref. 1]

The federal annual standard of 50 $\mu g/m^3$ is based on the arithmetic mean of the PM_{10} measurements for the year assessed on a

site-by-site basis. To meet the federal 24-hour standard, a site must not exceed a level of 150 $\mu g/m^3$ more than once per year, averaged over three years. As an example, a site may exceed the 24-hour standard twice in one year, but not exceed that standard for the next two years. In this case, the three-year average is less than the one exceedance allowed per year and therefore that site would be considered in compliance with the federal 24-hour standard. [Ref. 1]

The standards for the State of California are more stringent than those of the federal government. For a site to be in compliance with the California annual PM_{10} standard, its mean of PM_{10} concentrations must not exceed 30 $\mu g/m^3$. To comply with the 24-hour California state standard, a site cannot exceed a concentration of 50 $\mu g/m^3$ more than once a year, based on a three-year average. [Ref. 1]

There is a provision in both the federal and state standards to exclude "exceptional events" when determining violation or compliance with standards. Exceptional events are very high concentrations of PM_{10} caused by an event beyond regulatory control. Examples include particulates from structure fires, forest fires or dust storms.

The Bay Area meets the federal annual standard and is close to meeting the California standard. However, the Bay Area has exceeded the federal 24-hour standard four times since 1990. Additionally, data from 1992 show that the Bay Area exceeds the California 24-hour limit from 35 to over 70 days per year, depending on the collection site. [Ref. 3]

Though 1995 data showed improved compliance with the California 24-hour standard, there were still seven days in which the

daily standard was exceeded. But, 1995 data revealed no levels over the Federal 24-hour standard. Note that PM_{10} is measured every sixth day, so actual days of non-compliance can theoretically be six times greater than the number recorded. [Ref. 4]

F. WOODSMOKE

Homeowners in residential areas typically burn wood for the aesthetic beauty of a lit fireplace and to heat their residences. Though some citizens realize that the by-product of burning wood, woodsmoke, is a form of air pollution, most have little or no knowledge as to woodsmoke's effect on the air quality.

Complete combustion gives off heat, light, carbon dioxide and water vapor. In most cases wood burns only partially, producing the normal combustion by-products as well as carbon monoxide, nitrogen dioxide, volatile organic compounds and PM_{10}.

PM_{10} (Inhalable Particulate Matter) is composed of microscopic solid or liquid particles 10 microns in diameter or smaller. Woodsmoke is primarily made up of very small droplets of condensed organic vapors (wood tars and gases), which are unburned fuel that escape from a fire. As wood burns, it first boils off any moisture that is present in the wood. As the wood "cooks," it produces volatile gases, tars, and charcoal. Once a fire reaches approximately 600^0 F, the escaping gases start burning. However, the wood charcoal does not start to burn until the log reaches $1,000^0$ F. Most of the wood's tars and gases will escape unburned, because there is not enough heat ($1,100^0$ F) or oxygen close to the wood to ignite them. [Ref. 5]

The amount of PM_{10} pollution from one non-EPA certified woodstove is approximately 60 grams per hour, though newer

woodstoves and woodburning fireplace inserts certified by the EPA produce approximately 6 grams per hour. [Ref. 5]

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III. AIRDAS REMOTE SENSING SYSTEM

A. BACKGROUND

The Airborne Infrared Disaster Assessment System (AIRDAS) is a four-channel, multi-spectral scanning sensor originally designed to overcome limitations of previous remote sensing systems used in documentation of forest fires and other natural or human-caused disasters. Airborne remote sensing systems currently available to Ames engineers and scientists were designed as prototypes of operational and future remote sensing space systems. An example of one of these systems was the Daedalus AADS-1268 12-channel, multi-spectral scanner. The Daedalus scanner is a Thematic Mapper Simulator (TMS) currently flying on NASA's ER-2s. Though the Daedalus TMS and other scanners have been used for earth sensing assessments, including fire research, they have not been optimized for that application. Noticeable shortfalls include their inability to define small temperature differences in intense wildfires and airborne platform installation restrictions due to their large size and weight. [Ref. 6]

B. REMOTE SENSING

"Remote sensing" is defined as the acquisition of information about an object without physical contact between the sensor and the object. The human eye is the simplest remote sensor. However, "remote sensing" usually refers to gathering data about an object using multi-spectral sensors. Multi-spectral sensors, such as those used in AIRDAS, exploit the particular characteristics and properties of

electromagnetic radiation at various wavelengths using specific regions of the electromagnetic spectrum. [Ref. 7]

1. Electromagnetic Spectrum

In remote sensing, it is typical to categorize electromagnetic waves by their wavelength. The most commonly used unit to measure wavelength in the remote sensing community is the micrometer (μm). Figure 3-1 shows the useful portion of the electromagnetic spectrum, along with the various spectral bands, from the shorter wavelengths of cosmic and xrays at 10^{-6} μm, extending to the longer wavelengths of television and radio waves at 10^{9} μm and higher [Ref. 8]. The portion of the spectrum used most frequently by so called electro-optic remote sensing systems can be seen in the expanded scale of the electromagnetic spectrum shown in Figure 3-2.

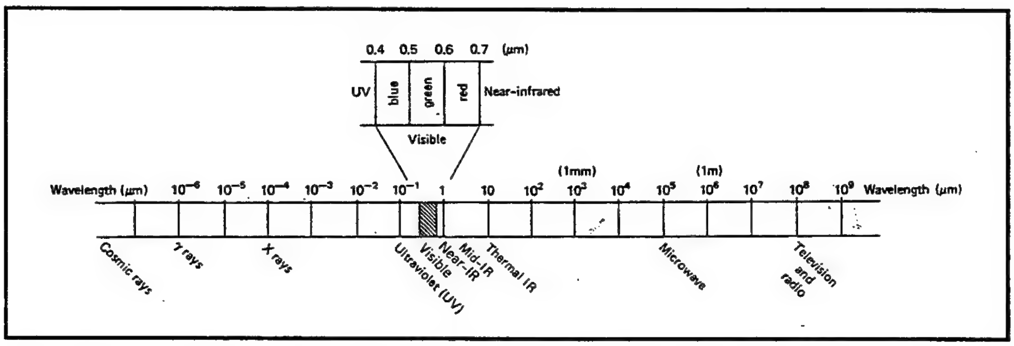

Figure 3-1. The Electromagnetic Spectrum. From Ref. [8].

The "visible" portion of the spectrum, namely what the human eye can see, stretches from about .4 μm to .7 μm. It is commonly divided into three color regions: blue, green and red. The shorter wavelengths, the blue region, extends from .4 μm to .5 μm, the green region from .5 μm to .6 μm, and the longer wavelengths, the red region, from .6 μm to .7 μm. Adjacent to the blue region of the visible

spectrum is the ultraviolet region and adjacent to the red end at longer wavelengths, is the infrared (IR) portion.

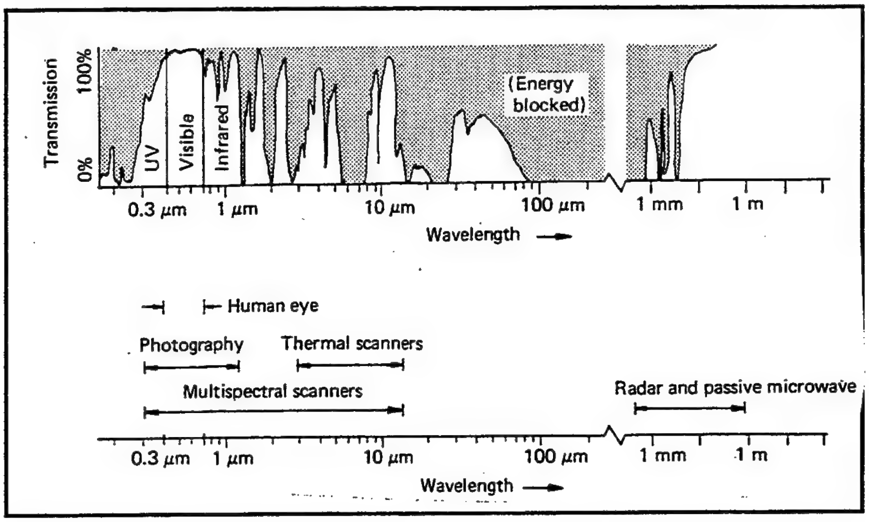

Figure 3-2. Major Spectral Regions Pertinent to Remote Sensing. From Ref. [8].

Multi-spectral scanners collect data throughout the ultraviolet, visible and infrared regions of the spectrum. Sensors collect the sun's reflected solar energy from about 0.2 μm to 2.5 μm. A transition region is present from 2.5 μm to 8.0 μm, where remote sensors collect both reflected solar energy and emitted thermal radiation. Thermal radiation is the primary source of energy collected by remote sensors between 8.0 μm and 14.0 μm. In this longer wavelength region of thermal radiation, sensors do not depend on direct solar illumination in order to detect and collect emitted energy. [Ref. 8]

a Infrared Region

The three most commonly used regions of the IR wavelength band are near-IR (NIR), midwave-IR (MWIR) and thermal or longwave-IR (LWIR). NIR waves range from 0.7 μm to 1.3 μm. Sensors in this region detect and collect the sun's reflected energy.

The MWIR region lies between 1.3 μm and 3.0 μm. Its energy is also related to the sun's reflected energy. At wavelengths longer than 3.0 μm lies the thermal-IR region. Of these three regions, thermal-IR's energy is directly related to heat. [Ref. 8]

Remote sensors that collect data in the visible and NIR regions have capitalized on the ability or inability of objects to reflect solar energy. For example, in the visible region, energy associated with blue light is absorbed by chlorophyll. Data gathered in this region can be used to classify various types of vegetation. In the red region of the visible spectrum, soil and vegetation are easily classified due to their different reflective capabilities. [Ref. 8]

MWIR electromagnetic energy is a mix of reflected solar energy and emitted energy. Sensors in this region can be used to "see through" or penetrate smoke to obtain measurements of surface temperature. [Ref. 7]

In the thermal-IR region, thermal emission is the predominant source of electromagnetic energy. Sensors operating in these bands are not constrained by the requirement for solar illumination. Thermal-IR is often used to classify and pinpoint hotspots while combating forest fires. It can also provide unique identifications of soil types and ground cover. [Ref. 7]

b. Emissivity

Emissivity is the measure of an object's efficiency as an absorber or emitter of black body radiation at a specific wavelength. Emission characteristics of materials are obtained by comparing the radiant emittance of the material or object to the radiant emittance of a blackbody at the same temperature given by:

$$\varepsilon = \frac{E_{material}}{E_{blackbody}}$$ Equation 3-1. From Ref. [9].

where

ε = emissivity of an object (dimensionless)

$E_{material}$ = emitted radiance of an object at a given temperature in W/m^2

$E_{blackbody}$ = emitted radiance of a blackbody at the same temperature in W/m^2

Plank's Radiation Law relates the spectral characteristics and magnitude of the emission to the temperature of the emitter at a given wavelength. For a blackbody this is given by:

$$E_{\lambda} = \frac{C_1}{\lambda^5[e^{(C_2/\lambda T)} - 1]}$$ Equation 3-2. From Ref. [9].

where

E_{λ} = spectral emission in W/m2 at a specific wavelength l

λ = wavelength in m

C_1 = first radiation constant 3.74×10^{-6} W m^2

C_2 = second radiation constant 1.44×10^{-2} m K

T = absolute temperature in K

All material at temperatures above absolute zero (0 Kelvin, or -273°C) emit black body radiation. The total energy emitted by an object is a function of the object's surface temperature. This is expressed by the Stefan-Boltzmann law as:

$$M = \varepsilon \sigma T^4$$ Equation 3-3. From Ref. [8].

where

ε = the emissivity of the object

M = total radiant exitance from the surface of a material in Watts/m^2

σ = Stefan-Boltzmann constant (5.6697 x 10-8 W/m^2 K^4)

T = absolute temperature of the emitting material in Kelvin (K)

The total energy emitted from an object varies as T^4, which means that as the temperature of an object increases, the emitted energy of that object increases rapidly.

2. Atmospheric Effects

An important factor in remote sensing is the atmospheric effects on radiance measured at the sensor. Since the atmosphere is not completely transparent, radiance measured at the sensor will not only be influenced by the earth's surface but also by the composition and thermal structure of the atmosphere. [Ref. 7]

Atmospheric conditions, such as clouds and turbulence, will have an effect on the amount of surface radiation seen by sensor, but the most important effect is that caused by "absorption bands." Absorption bands are regions throughout the electromagnetic spectrum where most of the surface radiation, whether reflected or emitted, is absorbed by atmospheric constituents. Several of these larger bands result from absorption due to water vapor and carbon dioxide (CO_2) [Ref. 7]. "Atmospheric windows" or transmission windows, are regions in the electromagnetic spectrum in which attenuation due to atmospheric gases is minimal, thus providing better observation of surface radiation. Remote sensing systems have carefully selected collection channels to coincide with these atmospheric windows. Figure 3-3 shows the various absorption bands

and transmission windows in the portion of the electromagnetic spectrum where most remote sensors operate.

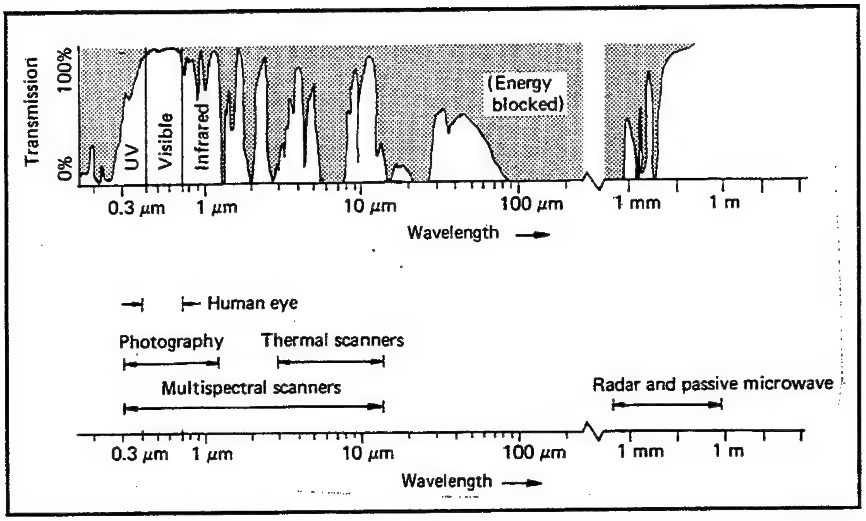

Figure 3-3. Major Spectral Regions Pertinent to Remote Sensing, Showing Atmospheric Transmission Windows (White) and Absorption Bands (Black). From Ref. [9].

C. AIRDAS

1. Description

AIRDAS was designed and built at NASA-Ames Research Center (Moffett Field, California). Funding and design of the initial elements of the system were provided through the Ames Basic Research Council's Director's Discretionary Fund and the United States Forest Service's Fire Research Laboratory. The NASA Ames Ecosystems Science and Technology Branch, High Altitude Aircraft and, Medium Altitude Aircraft and Engineering branches were involved in the conception, design, and construction of AIRDAS. [Ref. 10]

Scientists and engineers involved in the project focused on several themes while designing the system. They wanted to ensure that the system would be a valuable research instrument, while at the same time, provide cost-effective applications support for wildfires

research. Some of the criteria included: 1) use off-the-shelf components to reduce design time and costs and provide for duplicity of system manufacture; 2) make the total system self-contained and portable, incorporating all controls, displays and recording functions at a single station; and 3) be able to rapidly install, integrate and deploy the system on a small aircraft in order to reduce operating costs. [Ref. 10]

2. Channel and Detector Characteristics

The AIRDAS scanner was designed to make qualitative measurements of very high radiances (temperatures) often associated with forest fires. The scanner incorporates the optical system of a Texas Instruments (TI) RS-25 thermal line scanner. NASA Ames engineers re-configured the TI scanner to acquire 4-channel, 16 bit data [Ref. 6].

The AIRDAS system consists of four channels related to specific wavelength regions. Each channel incorporates a different detector element for data collection. Channel 1 has a detector element composed of a silicon (Si), channel 2 has an indium-gallium-arsenide (InGaAs) detector, channel 3 an indium antimonide (InSb) and the channel 4 detector element is mercury-cadmium telluride (HgCdTe). Channel 3 and 4 are co-located, with detector 3 on top of detector 4. This detector configuration was chosen to provide two adjacent, relatively wide-band channels. Thus, if narrow band filters are used on channel 3, then channel 4 data is compromised due to channel 3 detector's position relative to the detector of channel 4. Table 3-1 provides a summary of the four AIRDAS channels with associated detectors and wavelength regions [Ref. 6].

AIRDAS CHANNEL	DETECTOR TYPE	WAVELENGTH (μm)
1	Si	0.61-0.68
2	InGaAs	1.57-1.70
3	InSb	3.60-5.50
4	HgCdTe	5.50-13.0

Table 3-1. AIRDAS Channels, Detectors, and Wavelength Regions. From [Ref. 6].

There were several factors considered in selection of the specific wavelength coverage associated with each of the four AIRDAS channels. Generally, the collection regions were located within transmission windows to ensure that as much energy as possible was transmitted from the earth's surface to the sensor.

Channel 1 measures reflected energy in the red portion of the visible spectrum, channel 2 from the NIR region, channel 3 from the MWIR, and channel 4 from the thermal-infrared portion of the electromagnetic spectrum.

Each AIRDAS channel provides valuable and specific information when studying wildfires. Channel 1, being a visual channel, is useful in determining extent and movement of smoke plumes as well as surface physical features. Channel 2 is useful for the analysis of vegetative composition. Channel 3 was specifically chosen to penetrate smoke and determine wildfire temperatures. Channel 4 was chosen to collect surface temperature data.

Because the chimney of a lit fireplace primarily emits energy at thermal-IR wavelengths, we focused our collection and analysis on the data obtained through AIRDAS channels 3 and 4.

3. Airframe Integration

The AIRDAS digital scanning system is a self-contained, portable remote sensing system. NASA Ames engineers designed AIRDAS so that one person could easily install it in either a large or small aircraft. Integration on a fully compatible aircraft can be accomplished in less than one hour. Compatible aircraft include the NASA Ames Lear Jet, the L.A. County Piper Navajo, the National Center for Atmospheric Research (NCAR) Beech King Air, a Navy P-3 Orion, and a Brazilian Lear Jet. [Ref. 6]

The AIRDAS scanner port requires a 7-inch by 14-inch opening in the underside of the aircraft. Airframe interior room must be large enough to house the control rack and operator. The control rack is approximately 24 inches wide, 30 inches deep and 3-1/2 feet high. Power requirements for the AIRDAS system are 28V DC at 20 amps with the total system weight at approximately 270 pounds. Table 3-2 lists the system composition, power requirements and weight. [Ref. 6]

Power Requirements:	28 V DC @ 20 amps
Weight Head: **Rack:** **Total:**	80 pounds 190 pounds 270 pounds
Scanner Port Size:	7 inches x 14 inches

Table 3-2. AIRDAS System Composition. From [Ref. 6].

The AIRDAS system includes the Texas Instruments RS-25 optical head, the two-step linear pre-amplifiers, a sixteen bit digitizer, dichroic band-pass filters, an Ampro 386 computer for system control, an Exabyte 8500 5Gb tape output device, a Trimble TN2000 Global Positioning System (GPS) unit and a two-axis gyro [Ref. 6]. Figure 3-4 shows the basic components of a multi-spectral scanner.

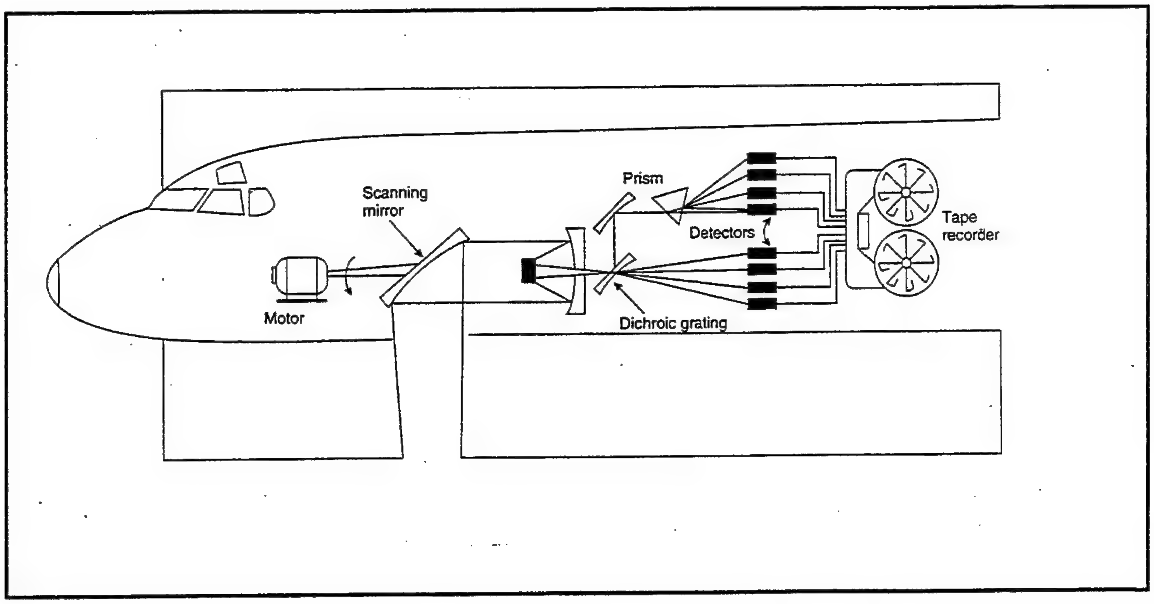

Figure 3-4. Basic Components of a Multi-Spectral Scanner. From Ref. [9].

The dichroic filters are used for narrowing the bandpass width of the individual detection channels and are easily changed and installed. The GPS receiver data is integrated with the scanner output and delivers encoded information on the location and relative position to the header file for each scan line. The two-axis gyro sends encoded aircraft pitch and roll information to the control system to allow for post flight data correction. The two-axis gyro provides information only in the pitch and roll direction, not in the yaw direction. A magnetic compass, within the AIRDAS system, assists in determining heading and allowing for geometric correction. The aircraft barometric altimeter information is included in the header information of the output data. Display of additional flight and mission parameters in the header information is possible, depending on airframe and installed equipment. Figure 3-5 shows the overall proportions of the AIRDAS electro-optics portion. Figure 3-6 shows

the complete AIRDAS system, including the optics head and the control rack. [Ref. 6]

4. Optics

AIRDAS is an across-track or "whiskbroom" type scanner. The scanning optics used on AIRDAS have a Field-Of-View (FOV) of 108 degrees across track, with an Instantaneous Field-Of-View (IFOV) of 2.62 milliradians [Ref. 6]. The FOV, also known as the Angular Field-Of-View (AFOV), or the scan angle, is used to determine the ground swath. The ground swath is the width of the ground strip recorded as a scan line. A scan line is one sweep of the scanner optics. The IFOV determines how much ground area the scanner can "see" at any given instant in time. This ground area is also known as the ground or "spatial" resolution. Typical IFOV's for airborne scanners range

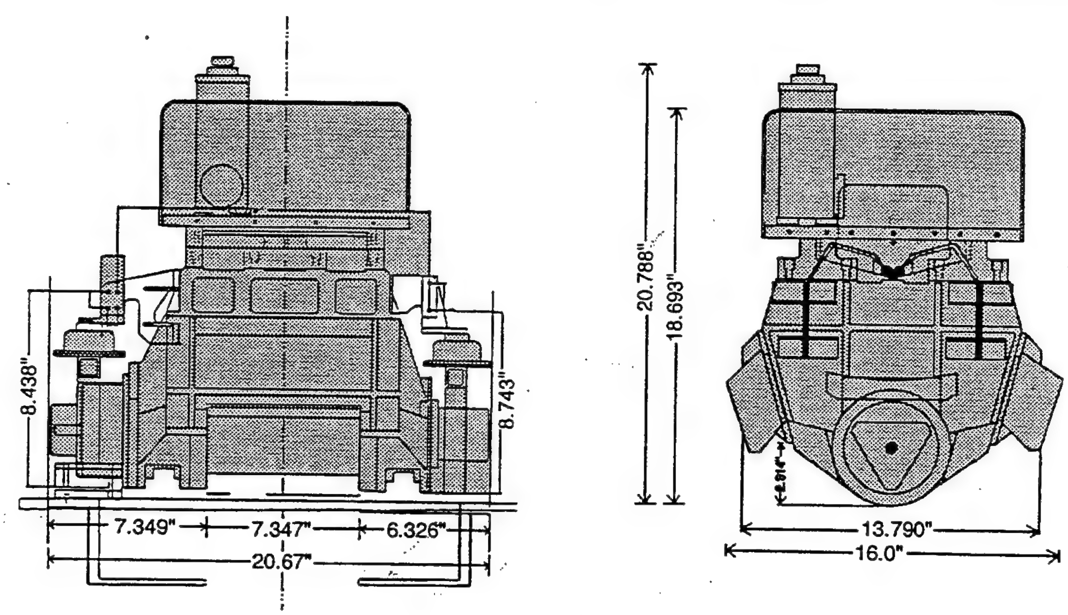

Figure 3-5. The AIRDAS Electro-Optics Design with Airframe Incorporation Measurements. From Ref. [10].

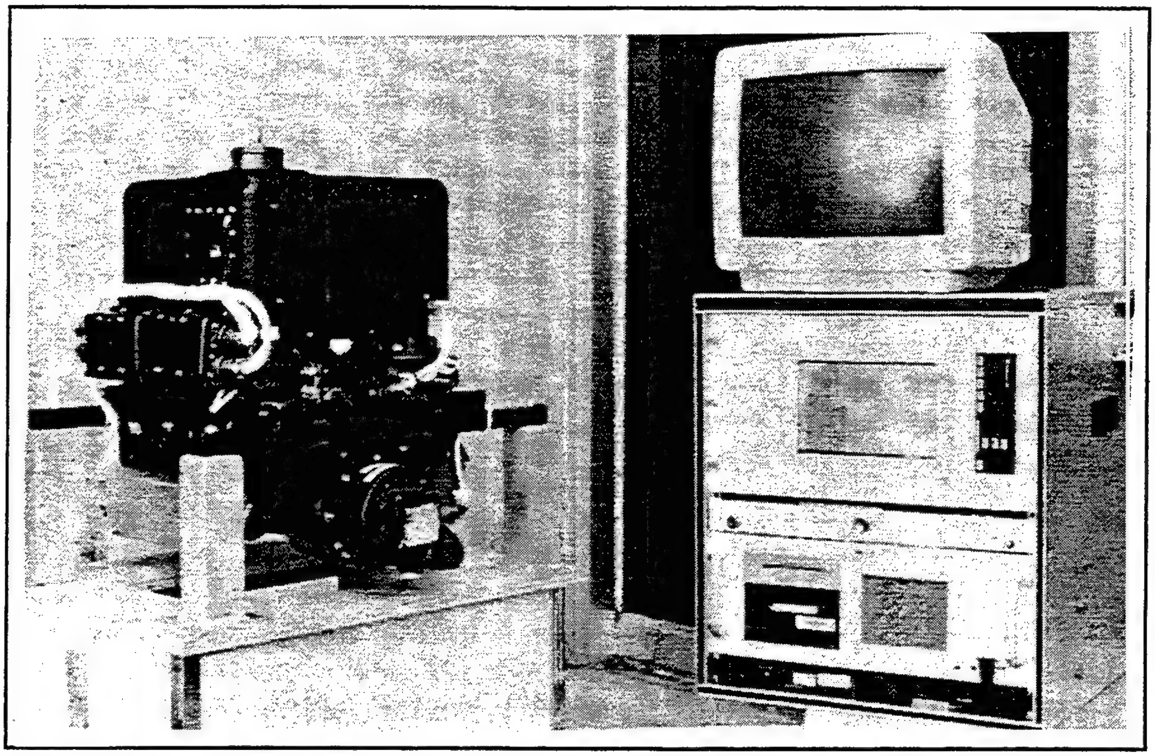

Figure 3-6. The AIRDAS System. The Optics Head is Located on the Left, with the Control Rack on the Right. From Ref. [9].

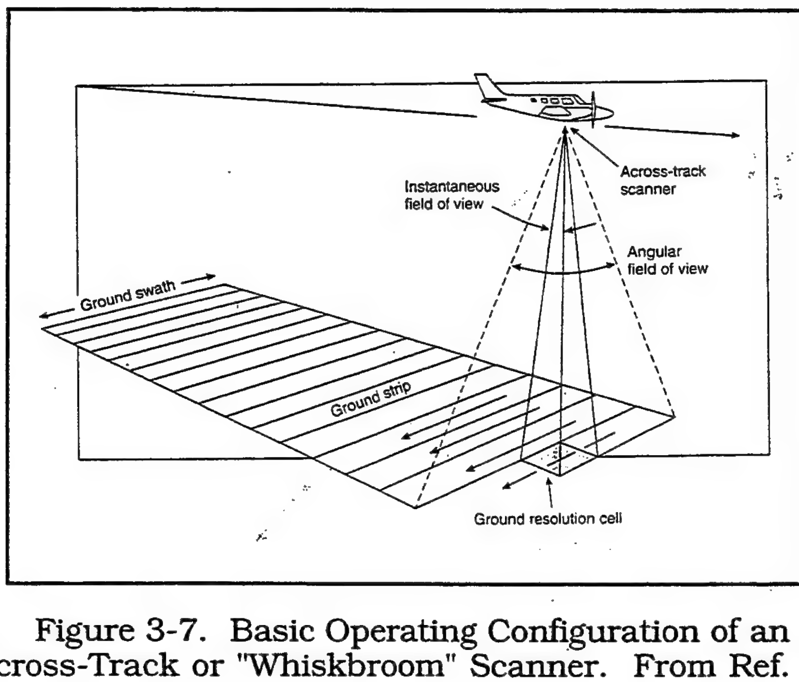

Figure 3-7. Basic Operating Configuration of an Across-Track or "Whiskbroom" Scanner. From Ref. [9].

between 0.5 and 5.5 milliradians. [Ref. 9] Figure 3-7 shows the basic operating configuration of an across-track scanner.

The AIRDAS system has a scan rate of 5 to 23 scans per second and can operate in a flight envelope from 3,000 to 34,000 feet above ground level (AGL) at aircraft ground speeds between 100 to 260 knots. The system has a digitalized swath width of 720 pixels in the across-track direction. Continuous data flow is acquired in the along-track direction as long as the scan rate is correlated with the ground speed. [Ref. 6]

5. Data Collection, Storage and Forwarding

The data acquired through AIRDAS is collected and stored on Exabyte 8 mm data storage tapes by an Exabyte 8500 recording device. Current storage capacity is 5 Gb, though data storage tapes may be changed inflight, providing for near continuous data collection. [Ref. 6] Extraction, formatting and processing of data stored on the Exabyte tapes will be covered in Chapter V.

The original design of the AIRDAS system incorporated a means to transmit data directly to a receiving station on the ground through a telemetry interface. A high-speed digital down-link delivers AIRDAS scanner data from the aircraft to a ground station. The data link consists of a transmitter sending bi-phase encoded digital data to a receiving antenna. Header information, i.e., GPS location and aircraft attitude (pitch, roll and yaw), is transmitted through a separate channel. This allows for real-time collection and processing of data, primarily used in combating wildfires. [Ref. 6]

In-work modifications to AIRDAS include upgrading the electronics package to increase the usable scan rate. At the present

time, the maximum scan rate is 23 lines per second. This upgrade, expected to be completed in the near future, will increase the scan rate to 60 - 70 lines per second. This will allow the AIRDAS system to fly at altitudes as low as 1000 ft, greatly increasing its ground resolution.

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IV. TEST PLAN DEVELOPMENT

Test plans are an important step in conducting any research project or experiment in which a variety of people and assets must be brought together at a given time to ensure successful collection of meaningful data. The primary purpose of a test plan is to communicate the following to all participants:

- What will be done during the test or experiment
- Why the experiment is being conducted
- How the experiment will be conducted
- What each participant is expected to complete

A secondary purpose of a test plan is to assist in organizing thoughts and actions into a coherent plan that will help in detecting any lacking, incomplete or unnecessary components. [Ref. 11]

Appendix A contains the final test plan for the conduct of this experiment.

A. OBJECTIVES

There were two objectives for this project. First, to determine whether or not airborne remote sensors could detect lit fireplaces well enough to count them, or to at least provide usable data to BAAQMD. Second, to find the most efficient way of determining lit fireplace density after detection. [Ref. 12]

In order to meet the objectives, an experiment was conducted to measure the level of effectiveness of an airborne sensor to detect lit fireplaces. There are several possible ways in which airborne remote sensors might be able to detect lit fireplaces. One is to detect the smoke plume, and the other is to detect the heat energy emitted by

the chimney. Detection of the actual smoke plume requires that a sensor be able to collect data in the visible spectrum. But, a clean burning fireplace emits little or no smoke plume, therefore, detection of a lit fireplace is best accomplished using thermal sensors.

B. EQUIPMENT SELECTION

The original study proposal specified the use of the NASA Ames C-130 Earth Resources Aircraft and its NS001 Thematic Mapper Simulator or Thermal Infrared Multi-spectral Scanner (TIMS) to conduct a survey over a large portion of the Bay Area. The proposed flight altitude using the NS001 was 2500 feet above ground level, producing a ground resolution cell of 1.9 m^2. Because of its limited scan speed, the TIMS would have required an altitude of 4000 ft AGL, producing a ground resolution cell of 3.0 m^2. [Ref. 12]

NASA cancelled the AMES C-130 program between the time the proposal was accepted and the time that the tests were scheduled to start, so neither the NS001 nor the TIMS thermal scanner was available for this experiment. The alternate system for this project was the AIRDAS multi-spectral imaging system. As noted above, the AIRDAS system can be installed on a variety of platforms. The platform chosen for this experiment was the NASA Ames Learjet, because of its co-location with AIRDAS operations at NASA Ames. This simplified the engineering, installation and equipment checkout required to integrate AIRDAS with the airframe.

THE NASA Ames Learjet, Model 24, was part of the Center's Airborne Observatory Program. The Learjet Model 24 is a corporate class, high-altitude, high-performance twin engine turbojet aircraft. It is an economical, quick-response platform with the capability to

incorporate and support a wide variety of airborne experiments. It's relatively small size and high thrust allow it to operate from many small to medium-sized airfields that are inaccessible to larger aircraft. [Ref. 13]

The Learjet has a service ceiling in excess of 45,000 feet, is capable of flying 1,700 nautical miles at cruise airspeeds up to 450 knots with a payload of 1,200 pounds. Payload weight is based on two pilots and two observers. If only one observer is required, additional instruments can be added. [Ref. 13] Because the AIRDAS system (including equipment rack and scan-head) weighed only 240 pounds, data collection flights often included an equipment operator and three observers, in addition to the pilots.

Figure 4-1 shows a photograph of the NASA N705 Lear Jet in a hangar at Ames Research Center, Moffet Field, California. The AIRDAS scanner head is mounted on the port side of the aircraft just below the door. Note that the pressure box on the lower half of the door, which houses the scanner, is not shown in the photograph.

C. GROUND RESOLUTION

The ground resolution cell is defined as the ground area the scanner “sees” at a given instant in time. When viewed on the digital imagery, the ground resolution cell is called the picture element or "pixel." Digital imagery is composed of a two-dimensional array of pixels, which correspond spatially to ground resolution cells.

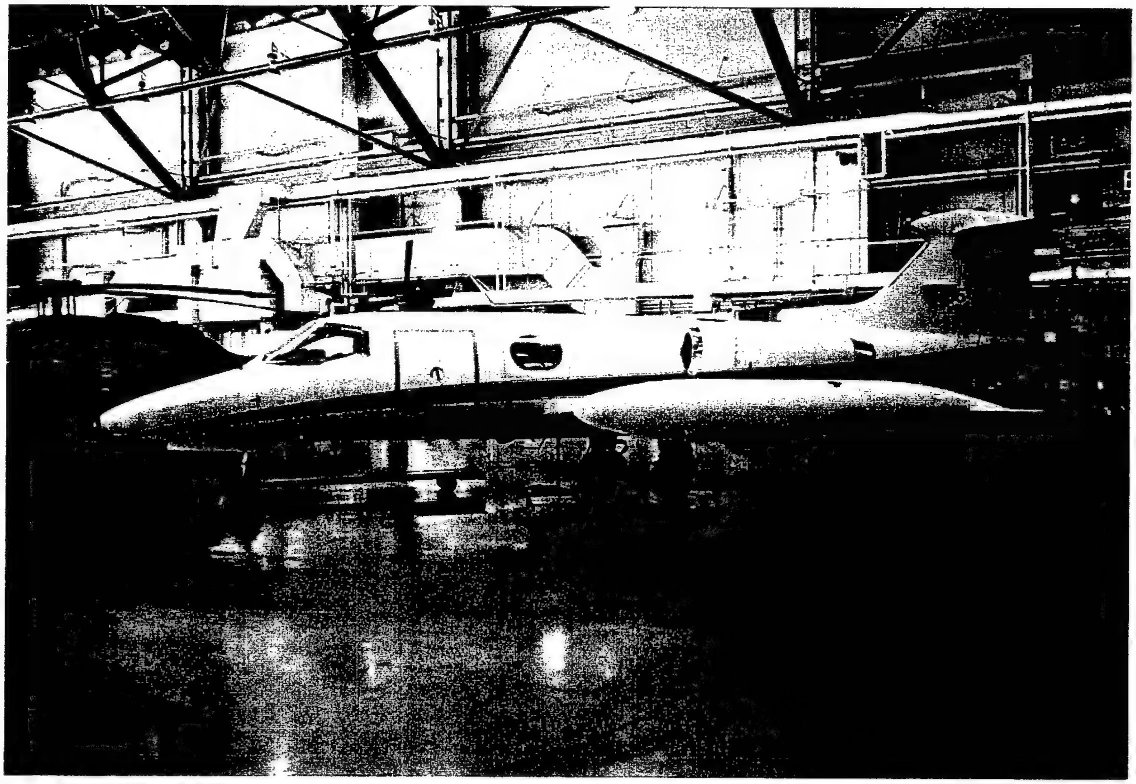

Figure 4-1. NASA Ames N705 LearJet Model 24.

The size of the ground resolution cell is primarily determined by the instantaneous field of view (IFOV) of the scanner optics described in Chapter 3 and the height of the sensor above ground. Given the IFOV and height above ground, we can calculate one side of the ground resolution cell using the following formula:

$$D = H \sin(b) \qquad \text{Equation 4-1.}$$

where

D = one side of the ground resolution cell at nadir

H = flight altitude above mean terrain

b = scanner's IFOV

note: Nadir is the point at which the scanner is "looking" straight down, i.e., the scan angle equals 0°.

Since b is small, sin (b) can be approximated as b and Equation 4-1 becomes:

$$D = Hb \qquad \text{Equation 4-2.}$$

Where b is expressed in radians. For AIRDAS, the area of the ground resolution cell at nadir is equal to D^2.

Several other factors must first be taken into account when determining the size of the ground resolution cell (or simply, "resolution") for AIRDAS. The scan rate optics has the greatest effect on the resolution of AIRDAS. The analog-to-digital conversion bandwidth of 25 KHz restricts scan speed of AIRDAS to approximately 22 scans per second [Ref. 10]. Scan speed in turn limits the required aircraft airspeed for a given height above ground by the following relationship:

$$n = (V)(1.688/H)(1/IFOV) \qquad \text{Equation 4-3. From Ref. [10].}$$

where

n = number of scans per second

V = maximum aircraft airspeed in knots to prevent gaps in the imagery

H = height above ground level in feet

IFOV = instantaneous field of view in radians

Figure 4-2 shows various altitude and airspeed combinations and the corresponding ground resolution cells (listed in the "IFOV" column).

The minimum airspeed that the Learjet can fly without stalling or causing too much motion of the sensor must also be taken into account when determining ground resolution.

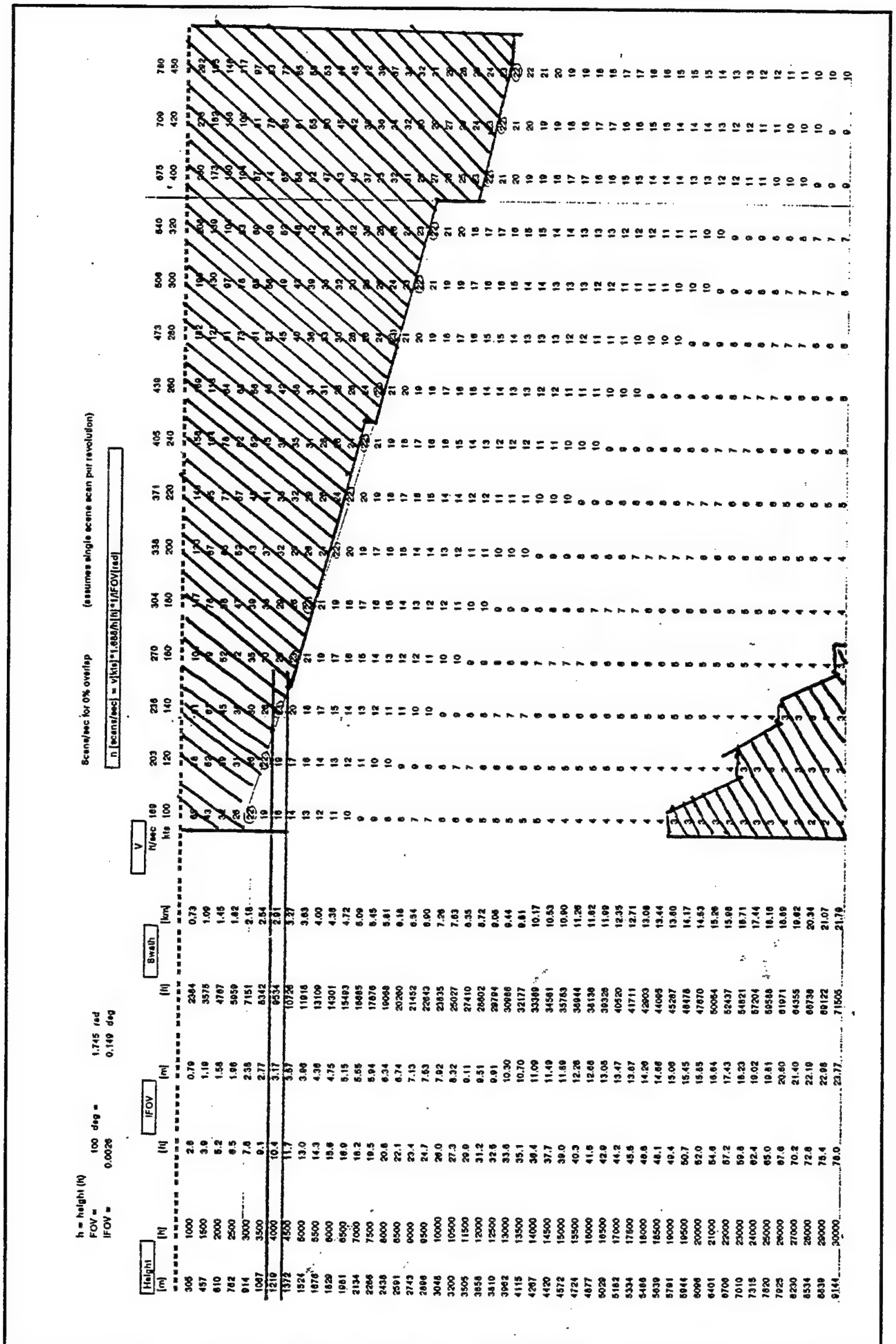

Figure 4-2. AIRDAS Ground Resolution for Various Combinations of Altitude and Airspeed. From Ref. [10].

Though we requested an airspeed of 160 knots to obtain the best possible ground resolution, the pilots determined that the slowest safe airspeed would be 180 knots. Referring Figure 4-2, an airspeed of 180 knots and a scan rate of 23 scans per second, results in a best possible resolution 3.96 meters (at nadir). [Ref. 10]

At 5000 feet AGL, a ground speed faster than 180 knots would not provide continuous coverage along the track. The AIRDAS scanner would not be able to scan fast enough to "see" the area being covered, thus creating gaps in the imagery. In this experiment, it was important to obtain information of the entire test area in order to ensure all control houses appeared in the imagery.

Though the ground resolution provided by the Learjet/AIRDAS system was lower than that originally proposed, the principal investigator and AIRDAS operators agreed that there was still a good chance that the system could detect lit fireplaces. Because AIRDAS records the average temperature (radiance) of a ground cell, study team members believed that the temperature difference between the fireplace chimney and the surrounding area would be sufficient to raise the temperature level of the pixel enough to make it easily discernible from other pixels.

D SITE SELECTION

Initial site selection was based on locations of BAAQMD ground sites used for air quality measurements. The instruments at these sites were situated in areas with a high density of residential neighborhoods and elevated levels of PM_{10}. Studying houses around these sites would enable BAAQMD to directly correlate the number and distribution of lit fireplaces with air quality (specifically, PM_{10}

concentration) at the time of data collection. One consideration during site selection was to keep the data collection areas relatively close to Moffet Field, in order to minimize flight time and thus conserve limited funding. The NASA/BAAQMD team decided to fly five data collection flights at two hour intervals each evening to study the effect of varying fireplace use throughout the evening. Typically, residential homeowners start and stop their fireplaces at all times during an evening, and we wanted a sample that more closely represented typical residential fireplace usage.

The initial plan was to collect data along two flight lines. The first line was a north-south track, starting just south of the San Jose International Airport, and extending for approximately four and one-half miles. The second line an east-west track, starting at Almaden Expressway and extending for approximately eight miles, through Los Gatos, paralleling interstate 85. Figures 4-3 through 4-5 show the two data collection areas plotted on American Automobile Association (AAA) local area road maps [Ref. 14 and Ref. 15].

A third line, through a neighborhood in Redwood City, was added later. This line corresponded to an area in which an Environmental Protection Agency (EPA) scientist was conducting a neighborhood air quality that correlated air quality with the use of fireplaces. He determined fireplace usage by ground observation, viewing the plumes from lit fireplace chimneys with a flashlight.

The approximate positions of the three flight lines were initially plotted on the VFR Terminal Area Chart of San Francisco [Ref. 16].

Figure 4-3. Fireplace Study Area #1, Campbell, CA. From Ref. [14].

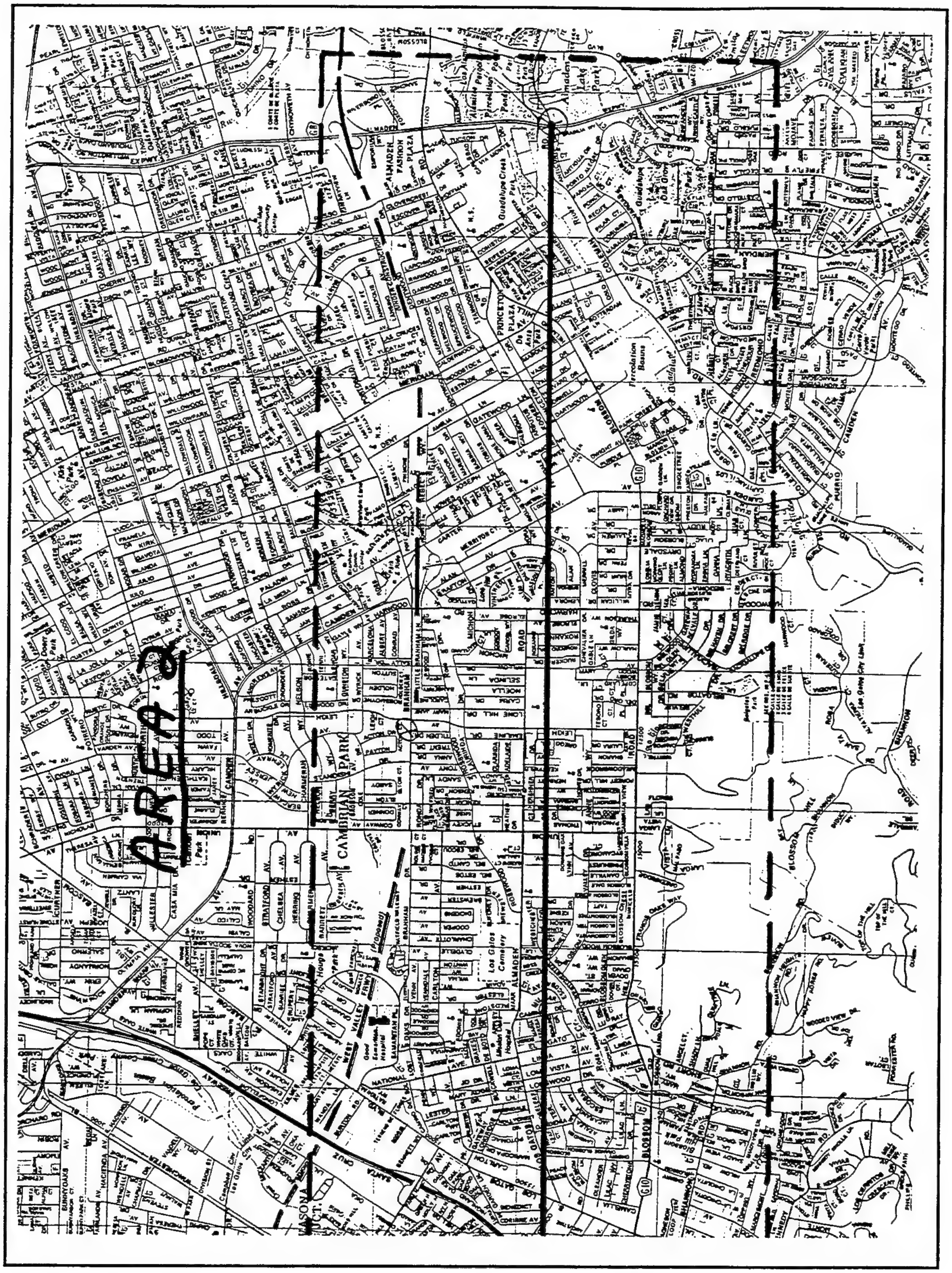

Figure 4-4. Eastern Portion of Fireplace Study Area #2, Los Gatos, CA. From Ref. [15].

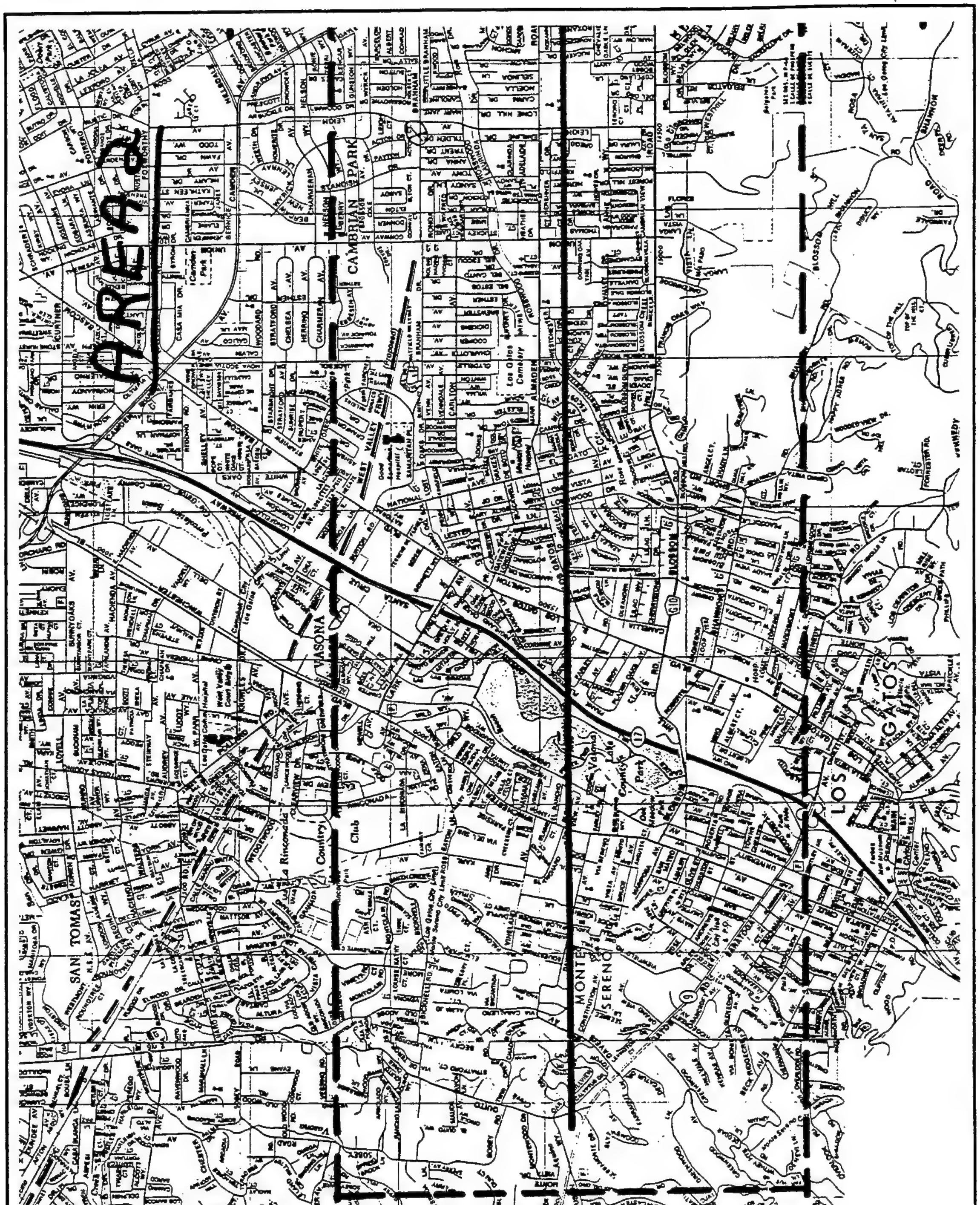

Figure 4-5. Western Portion of Fireplace Study Area #2, Los Gatos, CA. From Ref. [15]

VFR Terminal Area Charts are helpful in determining any airspace use restrictions that apply. This was important because of the high volume of San Francisco Bay Area air traffic in and around the intended collection sites and the sites' proximity to major international airports. Additionally, because of the small scale (1:250,000), this chart provided a means to plot the three data collection lines at one time, allowing pilots to easily visualize how they were spatially related to one another. Figure 4-6 shows the three data lines plotted on the VFR chart.

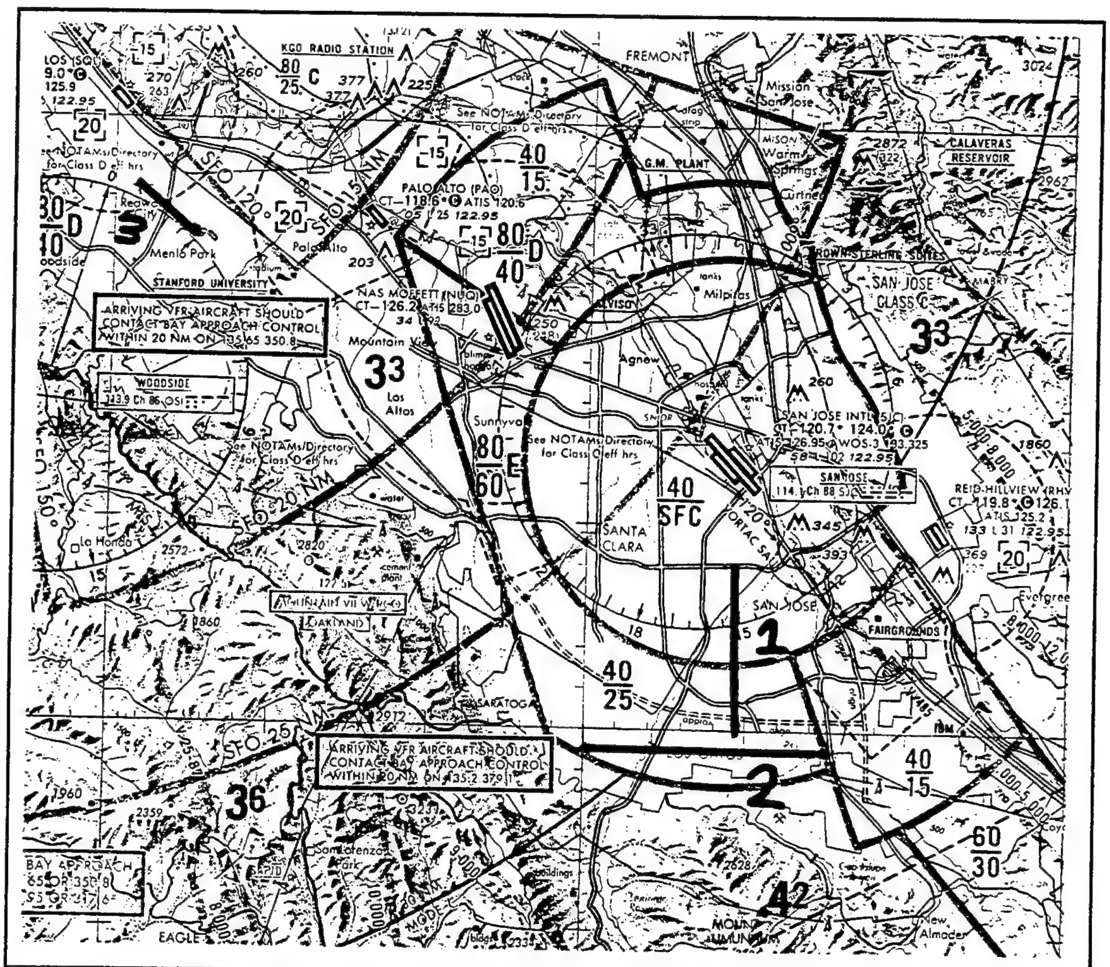

Figure 4-6. Data Collection Lines Plotted on a Portion of the San Francisco VFR Terminal Area Chart. From Ref. [16].

Another step in the site selection process was to obtain 7.5 Minute Series (Topographic) maps from the United States Geological Service (USGS) office in Menlo Park California [Ref. 17, Ref. 18, Ref. 19, Ref. 20, Ref. 21, and Ref. 22]. With a scale of 1:24,000, topographic maps are most useful in relating the ground features of interest to latitude and longitude. Endpoints of data collection lines were placed specifically to coincide with geographical landmarks such as streets and lakes. Aligning the flight lines and endpoints with major roads or other geographical landmarks helped the pilots stay on track during the actual data collection flights. This also provided a backup to the aircraft navigational instruments. Table 4-1 shows a list of the USGS topographic maps used with each data collection line number.

7.5 Minute Series Map	Data Collection Line
San Jose West Quadrangle	1 & 2
San Jose East Quadrangle	1
Los Gatos Quadrangle	2
Castle Rock Ridge Quadrangle	2
Santa Teresa Hills Quadrangle	2
Palo Alto Quadrangle	3

Table 4-1. USGS Maps and Corresponding Line Numbers.

From the 7.5 minute USGS charts, the latitude and longitude of the flight line endpoints for the three data collection sites could be obtained. The three sites were named for the areas in which they were located. The latitude and longitude for the three flight lines that bisected the collection areas were:

Line #1: Campbell Area

Course: 180/360°

Endpoints: N 37 deg 19.00 min, W 121 deg 55.35 min

N 37 deg 15.00 min, W 121 deg 55.35 min

Line #2: Los Gatos Area

Course: 270/090°

Endpoints: N 37 deg 14.60 min, W 121 deg 52.50 min

N 37 deg 14.60 min, W 122 deg 00.00 min

Line #3: Redwood city Area

Course: 310/130°

Endpoints: N 37 deg 27.10 min, W 122 deg 12.50 min

N 37 deg 28.25 min, W 122 deg 14.25 min

E. GROUND SWATH

Once the actual endpoints of the data collection lines were established, we had to determine how wide an area to examine. Width of the data collection areas was based on: 1) the requirement to collect enough data to make the results of the experiment viable and 2) the limitation that the sensor would "see" a limited ground swath. Because the lines passed through high-density residential areas, the number of houses available for analysis was more than sufficient.

The second factor, ground swath or swath width, is the width of the ground strip recorded as a scan line when using across track scanners such as AIRDAS. Ground swath is determined by the sensor collection mirror's angular field of view (AFOV), or scan angle, and the sensor's height above the ground. Ground swath can be calculated using the following formula:

$$S = 2 \tan(\theta/2)\,(H) \qquad \text{Equation 4-4. From Ref. [9].}$$

where

S = ground swath

θ = angular field of view

H = sensor altitude above ground level

As noted above, the lowest height above ground level that the AIRDAS/Learjet system could fly was 5,000 feet, due to scan rate and airspeed restrictions. The AFOV of AIRDAS is 108 degrees. The expected ground swath for this experiment is then:

$$S = 2 \tan (108/2) (5{,}000 \text{ feet})$$

$$S = 13{,}764 \text{ feet}$$

The imagery will become increasingly spatially distorted as the scanner optics turn away from nadir. This distortion can become severe at the outer edges of the field of view. Because of this, mission planners typically limit the data analysis to one-half mile on either side of the flight line (for an altitude of 5,000 feet). This ensures a one mile wide swath of relatively non-distorted thermal imagery.

F. GROUND TRUTHING

Ground truthing is the process by which remotely sensed data is verified by comparing it with *in situ* data or known information about the object being studied. To determine the temperatures that could be expected from a lit fireplace chimney or chimney exhaust, the principal investigator made temperature measurements of three typical lit fireplace chimneys and exhausts. These temperature measurements would provide a quick check of the temperatures recorded by AIRDAS.

Conducting a ground survey using control houses, in which fireplace usage would be known at the time of flights, would provide a

means to verify that a "detected" lit fireplace on AIRDAS thermal imagery was actually a lit fireplace and not another heat source.

1. Ground Tests

Prior to actual airborne data collection, a ground test conducted by the principal investigator determined representative chimney surface temperatures expected during the data collection flights. This data allowed the AIRDAS operator set the temperature range. The principal investigator used a Raytek ST4L portable, handheld, Mini Infrared Thermometer to make temperature measurements. The Mini Infrared Thermometer measures the radiometric surface temperature of an object without requiring direct contact of the instrument with the surface. Specifications of the Infrared Thermometer are listed in Table 4-2.

Characteristics	Specifications
Temperature Range	0 to 750°F (-18 to 400°C)
Accuracy	+/- 2% of reading or +/- 3°F (2°C) whichever is greater
Repeatability	+/- 1% of reading, +/- 1 digit
Distance Ratio	8:1 (i.e., instrument 8 inches from surface will see 1 inch area)
Response Time	500 msec
Spectral Response	6 - 16 microns
Temperature Display	1°F or °C, switch selectable
Ambient Operating Range	0 to 120°F (-18 to 50°C)
Power	9V Alkaline or Lithium Battery
Dimensions	5.4 inches (13.5 cm) L x 1.6 inches (cm) W x 7.7 inches (19.5 cm) H
Weight	9.5 oz (270 gm)

Table 4-2. Specifications of Mini Thermal Infrared Thermometer. From Ref. [23].

One purpose of this ground test was to determine representative temperatures of the chimneys, chimney caps, chimney exhausts and the surrounding roof areas.

The AIRDAS sensor actually indicates a single average reflected or emitted energy level for an entire ground resolution cell; it cannot distinguish between different objects within the same cell. Thus, any rise in temperature (i.e., energy) within the cell would cause the average temperature of the cell to increase. This increase in temperature would aid in the detection of a lit fireplace by increasing the temperature contrast between adjacent, cooler cells.

The ground test was conducted on three separate houses with lit fireplaces. The results of this ground test are contained in Appendix B. The first set of data (14300 North Alpine Road, Lodi, CA) showed very little difference in the temperatures of the chimney and the surrounding roof compared to the outside air temperature (OAT). The second set of data (14170 North Alpine Road, Lodi, CA) showed an approximate 10°C difference between the chimney and nearby roof area (3 feet from chimney). The third set of data (1515 Kahler Court, San Jose), showed approximately the same difference (4-8°C) between chimney and surrounding roof area. But, this chimney had a metal cover over the fireplace flue as well as a metal cover over the entire chimney. When readings were obtained from the metal covers, the temperature difference between the surrounding roof and the metal flue cover was nearly 70°C, with the metal chimney cover reading 35-45°C warmer than the roof. Additionally, when the sensor was pointed directly into the flue gas, it showed a temperature of 90°C.

The results from this ground test suggested that AIRDAS would most likely detect energy emitted from a chimney cover or exhaust rather than from the chimney bricks, as was initially believed. Because of the small difference in temperatures between a chimney and surrounding roof, the resultant rise in the average temperature of the pixel was limited. A small difference in average pixel temperatures would make lit fireplace detection difficult.

In order to validate the remotely sensed data acquired by AIRDAS, the research team conducted ground surveys in conjunction with data collection flights. The method used to obtain ground survey data was to seek out volunteers who resided in the test areas and were willing to provide information on fireplace usage during AIRDAS data collection.

a. *Volunteer Solicitation*

There was an initial concern as to how the general public would perceive the purpose of the lit fireplace detection experiment. One concern was that the public would view over-flights of their homes by imaging equipment as an invasion of privacy. The other concern was that the public would feel that this experiment to detect lit fireplaces was a precursor to legislation regulating fireplace usage or as a method to enforce future regulations.

Investigators made the initial requests for volunteers through several media sources within NASA Ames Research Center. Additional factors made Ames employees desirable volunteers. One of these was that the test areas were located in communities in which many Ames employees resided. The second factor was that many Ames employees were scientists, engineers and technicians involved

in some way with experiments or research on a daily basis and thus would be more willing and dependable volunteers for this experiment.

Solicitation for volunteers was first made through the Ames Center Director Bulletin, a daily electronic mail posting for all NASA Ames employees. The second request was through the Ames Astrogram, a weekly newsletter distributed to all NASA Ames employees [Ref. 24].

Response was better than expected, with volunteers eager to help and positive about the experiment as a whole. The NASA Ames Public Relations Office then prepared a press release for distribution to local radio and television stations and newspapers [Ref. 25].

The press release was picked up by the San Jose Mercury News and published as a front page story (see Appendix D) [Ref. 26]. Again, the response was greater than expected. Callers volunteering for the study were concerned about the local air quality and eager to help NASA scientists in the experiment. Nearly forty qualified residents volunteered their houses for the study. Approximately thirty other people called to volunteer, but they did not live within the collection area boundaries. In addition, two radio stations requested interviews with the principal investigator.

Volunteers gave their telephone number, address, and information about their fireplace and fireplace usage. Names were optional and addresses were kept confidential. Volunteers were contacted on the day before, or on the day of tests to inform them that data collections flights would take place and to inquire as to their intention to participate. It was not important for all volunteers to light

their fireplaces for the duration of the data collection. The important data was the time that fireplaces were ignited and the time that the last fuel was added. Also important were volunteers who were unable to participate. This would provide some control houses with heat sources limited to other than fireplaces.

b. *Control House Identification*

There was a requirement to be able to readily identify the control houses on the thermal imagery. To satisfy this requirement, an investigator conducted a survey of each home. Data collected included the location of the house relative to the nearest intersection and its position relative to the street. Additional information obtained by the investigator included the location and number of chimneys on each house. The location of the chimneys would provide validation as to the position of a lit fireplace detected on a control house when using thermal imagery.

To further aid in the placement of control houses on the thermal imagery, the principal investigator decided to obtain aerial photographs of the collection areas. Aerial photographs provided an initial visualization as to how the thermal imagery would appear. Once control houses were identified on the aerial photographs, their relative position in relation to streets and other landmarks would allow for quicker identification on the thermal imagery.

To obtain the aerial photographs of the collection areas, an Aerial Photography Inquiry Form submitted to the USGS office in Menlo Park, California, specified the areas of interest, detail, scale, and date of photograph. The large scale would enabled visual identification of chimneys on non-control houses. This would help

confirm lit fireplace detection on thermal imagery corresponding to houses not participating in the experiment. Because most of the collection areas covered established neighborhoods with little or no new construction, photographs no more than three years old were acceptable.

In response to our inquiry, the USGS provided a list of photographs covering the study areas of interest. This list included date, scale, film type, and organization responsible for the photographs. The USGS does not provide aerial photographs because the photographs are considered proprietary material. They do provide a pamphlet that lists the addresses and phone numbers of the agencies that own the photographs [Ref. 27].

Pacific Aerial Surveys of Oakland, California had the most appropriate set of photographs for this study. A visit to their offices provided an opportunity to view available photographs to include different scales and enlargement sizes. Selected photographs consisted of nine by nine inch, 1:12,000 scale prints, enlarged twice to a size of thirty by thirty inch, with a scale of 1:3,000. These provided sufficient detail of houses and other features, while at the same time providing a "big picture" representation of the study areas. Table 4-3 provides a listing of the aerial photographs obtained through Pacific Aerial Surveys (PAS).

G. FLIGHT PLANNING

The test plan specified data collection along three data acquisition lines, five times during the course of the evening. Acquiring data throughout the evening would provide thermal imagery

at different ambient air and background temperatures. Additionally, not all volunteer participants would be able to light their fireplaces at

Study Area	PAS File #	Date of Photo
1	AV4625-25-74, 76 & 78	07 Nov 94
1	AV4625-126-72	07 Nov 94
1	AV4625-226-2 & 4	07 Nov 94
2	AV4625-23-79 & 81	07 Nov 94
2	AV4625-24-79 & 81	07 Nov 94
2	AV4625-25-79 & 81	07 Nov 94
2	AV4625-226-5 & 7	07 Nov 94
2	AV4625-27-75 & 77	07 Nov 94
2	AV4625-28-75 & 77	07 Nov 94
3	AV4515-15-9 & 11	01 Sep 93
3	AV4515-16-7 & 9	01 Sep 93

Table 4-3. List of PAS Aerial Photographs.

the commencement of data acquisition. This would allow side-by-side examination of thermal imagery of control houses with lit and non-lit fireplaces. By starting early in the evening and finishing early in the morning, the investigators hoped that they might observe trends showing how long it would take for a chimney to heat-up to the point where it would cause a pixel on the thermal imagery to stand-out, and then how long that pixel would be prone to detection after a fire was out.

The NASA Learjet Manager scheduled all Learjet activities. Flight dates and times were requested through submission of a Flight Request Form. The Learjet would fly the AIRDAS data acquisition lines at 5,000 feet over the three collection areas. Flights would originate and terminate at NASA Ames, Moffet field. Each flight would last about 30 minutes, with the first flight commencing at 1800. Additional

flights would occur at two hour intervals, taking-off at 2000, 2200, 2400 and 0200 hours.

Flights would be weather-dependent. The test plan required data collection flights occur on nights cold enough that many residents, in addition to our control houses, would be using their fireplaces. Additionally, there could be no fog or clouds below the flight level of 5,000 feet. Clouds, rain and fog will absorb most of the energy being emitted from the earth before it reached the AIRDAS sensors. Though the sky may be clear, standing water from a rain storm will also affect the thermal imagery due to a change in surface reflectivity and emissivity.

H. DATA DISPOSITION AND REDUCTION

Thermal imagery data collected by AIRDAS in flight was transferred to Exabyte tapes through an Exabyte 8500, 5 Gigabit tape output device. System operators provided two copies of each tape annotated with date, flight number and line number. In addition, the AIRDAS manager provided copies of the AIRDAS Mission Report, as well as an individual to assist with data reduction and thermal imagery analysis software usage.

Data reduction and analysis conducted at NASA Ames Research Center's Ecosystem Science and Technology Branch computing facility, used the ERDAS IMAGINE™ image processing software package.

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V. DATA COLLECTION, REDUCTION AND ANALYSIS

A DATA COLLECTION

The data collected for this study included: ground survey, airborne and environmental. Supplemental data consisted of readings taken of lit fireplace chimneys using a handheld IR thermometer (Appendix B). IR thermometer readings used in the mission planning process helped determine the temperature settings for AIRDAS.

1. Ground Survey

Two areas of ground survey data included: 1) information gathered through phone conversations with participants who volunteered to light their fireplaces as part of the control group, and 2) information obtained through visual inspection of each control house. Information obtained through interviews included:

- address of control house
- name of volunteer (optional)
- type of fireplace used during the study
- type of fuel normally burned
- whether or not they operated their fireplaces
- fireplace start time
- fireplace stop time (last log added)
- would they be willing to participate again

Visual inspection provided information about chimney placement on the control houses, in addition to house placement in relation to the nearest intersection. Chimney placement information, used during data analysis, verified that "hot" pixels visible on the imagery correlated with the actual chimney positions on the control houses.

Appendix D contains an inventory of control houses by area, listing fireplace type, chimney location and type of fuel burned.

Names, telephone numbers and street addresses of volunteer participants are not included in this paper, but will be retained by the principal investigator (Jeff Jenner, of NASA). This protects the confidentiality of volunteer participants who may not wish to be contacted by people other than research team members.

2. Airborne Data Collection

Airborne data was comprised of the information obtained during the NASA Learjet flights with the AIRDAS system installed and operating. The test plan called for five flights during the course of the evening, beginning at 1800, with successive flights launching at two hour intervals (2000, 2200, 2400, & 0200). Each flight included at least one of the investigators as a passenger in addition to the AIRDAS operator.

The first scheduled series of data collection flights, for the evening of November 28, 1995, was canceled due to weather. Any moisture in the atmosphere between the ground and the sensor, whether fog, rain or clouds, can absorb the emitted energy prior to reaching the AIRDAS sensor. Imagery obtained under these conditions would have been unusable for this study.

An equipment checkout and study area familiarization flight took place on December 6, 1995. This operation ensured that AIRDAS worked properly, after not being used since the end of the fire season in late September (1995). Additionally, the flight gave the pilots a chance to become familiar with the area, to determine the best route and to determine approximate flight time required per sortie.

Equipment operators encountered no problems with AIRDAS during the equipment checkout and familiarization flight. However, they conducted the mission without the presence of either investigator due to a late break in the weather and subsequent launch on short notice.

Weather caused the cancellation of a second attempt at collecting thermal imagery on December 8, 1995. In this instance, the fog at NASA Ames (Moffet Federal Airfield) resulted in a ceiling below the minimum required for the safe take-off and landing. Unfortunately, calls to volunteer participants to inform them of the cancellation of data collection flights for the evening revealed that weather in the study areas appeared clear. Rain caused the cancellation of another flight on December 11, 1995.

The first AIRDAS imagery collection flight occurred on December 15, 1995. The night's first flight launched at 1700, an hour earlier than originally planned. Due to heavy air traffic in the San Francisco Bay Area in the early evening, the pilots requested launch one hour prior to the scheduled takeoff. The earlier takeoff time allowed easier access to the study areas by allowing the pilots to fly under Visual Flight Rules (VFR) rather than Instrument Flight Rules (IFR), in which they would have been under the positive radar control of an air traffic controller. Positive radar control requires that aircraft fly at given altitudes and headings as directed by air traffic controllers.

Only two of the five flights scheduled actually occurred, the first at 1700, and the second at 1900. A Federal government shutdown caused the cancellation of the remaining flights. NASA Ames required all personnel to secure at 2100 Pacific Standard Time in order to

comply with the shutdown of the Federal government at midnight Eastern Standard Time.

During the flights on December 15, the Learjet also carried a "Radiance 1" IR camera manufactured by Amber Electronics. Lawrence Livermore Labs furnished the IR camera, commonly referred to as the "InSb" camera, named after its detector element, indium antimonide. The intention was to test the IR camera's capabilities for use on new projects and to compare its imagery to that of AIRDAS.

An initial view of the imagery onboard the aircraft, during data collection, and a post-flight examination of the unprocessed 8-bit data showed many objects that appeared to be white or lighter shaded pixels, visible in the residential neighborhoods. System operator and study personnel initially assumed that these pixels corresponded to lit fireplace chimneys, since most were located in residential neighborhoods.

AIRDAS personnel supplied investigators with post-flight AIRDAS Mission Reports for each flight [Ref. 28 and Ref. 29]. The AIRDAS Mission Report logsheets included aircraft information such as airspeed, altitude, takeoff and landing times, as well as sensor scan rates and scan line counts for each area. Also included were remarks concerning any significant events or failures of the sensor system. From the mission report of the second flight we learned that the Gyro circuit breaker "tripped" to the open position during the first data acquisition line and could not be reset [Ref. 29]. Consequently, data acquired from collection areas 1, 2 and 3 from the 1900 flight could not be corrected for aircraft roll during data reduction.

Though it appeared from the initial analysis that usable data had been collected on the December 15 flights, the principal investigator still desired to conduct a complete set of flights, as specified in the test plan.

A second series of data collection flights, scheduled for January 17, 1996, never launched due to a Learjet equipment malfunction. The aircraft battery did not have the required charge and, without a spare or time to recharge the battery, prevented the airplane from flying.

Five data acquisition flights took place on January 22, 1996, without major incident, though there were several delays, one caused by air traffic congestion and another by a minor AIRDAS malfunction. Summaries of each flight are contained in the AIRDAS Mission Reports [Ref. 30, Ref. 31, Ref. 32, Ref. 33, and Ref. 34].

Several flights included additional AIRDAS data collection in support of other projects and follow-on fireplace density measurement studies. During the flight at 2000 hours, pilots flew a line parallel to the Los Gatos study area, which would help to determine the time, coverage and spacing that must be considered when performing actual large area surveys required for residential lit fireplace density. The midnight flight included a line of thermal imagery acquisition over Market Street in San Francisco. Results would determine whether or not AIRDAS could detect steam leaks in underground piping. The flight at 0200 hours included collection of thermal imagery of the grounds of a school for the deaf in Fremont, California. On a daily basis, this school had been losing large volumes of hot water from their hot water distribution system, most of which was located

underground. The AIRDAS manager believed that the thermal imagery would reveal the location of the leak.

3. Environmental Data

Appendix E contains the environmental for data December 15, 1995, and January 22 and 23, 1996. Information was collected at hourly intervals by six BAAQMD meteorological towers located in or near our study areas. Data collected at each location included the wind speed, wind direction, temperature in °F and relative humidity.

In general, ambient air temperatures during the evening of December 15 appeared warmer than normal for that time of year in the Bay Area. Temperatures at the towers read in the mid 50's (°F) at 1700, dropping to the lower 50's by 2000, with winds from the northwest at about 10 knots.

Colder temperatures prevailed on January 22 and 23, 1996. Temperatures were in the lower 50's to upper 40's at 1700 hours, dropping to the low 40's and the mid to upper 30's by early morning. Wind originated from the northwest at around 15 knots, but by 0200 hours had dropped to less than 5 knots.

B. DATA REDUCTION

Analysis of the thermal imagery required data transformation from the format collected by AIRDAS to a form compatible with image analysis software. AIRDAS data was recorded with an Exabyte 8500, 5 Gb tape output device, as signed 16 bit data and stored on Exabyte 8 mm data storage tapes. Formatting the data for the image analysis software required the use of three intermediate software programs. A SUN SPARC workstation, located in the Ecosystems Lab at NASA

Ames, performed downloading, integration, formatting and image analysis.

The first step of the reduction involved examining the imagery using a "quicklook" program. The quicklook program is a tool developed by the AIRDAS operators to view AIRDAS 8 bit, uncorrected imagery to provide users with a quick post-flight view of the data. Since AIRDAS collected data prior to and well past our actual study areas, the quicklook program provided an expeditious method to narrow the area of interest, avoiding the need to upload excessive data. From this imagery we were able to view the boundaries of the collection areas and extract the corresponding digital line numbers. This information was then used as an input to the next step of the process.

Step two involved using the first of two programs developed by the United States Department of Agriculture (USDA) Forest Service, Riverside Fire Research Lab, California. EXTRACT (version 2.0.3a, May 3, 1995) retrieved specific flight data segments from the AIRDAS data source file, using the boundary line numbers obtained from step one as inputs. This program also performed byte swapping of the AIRDAS data and output this data in the band interleaved by pixel (BIP) format. EXTRACT allows 680 pixel, across-track data retrieval and an unlimited along-track retrieval.

The third step involved the use of CREATE IMAGE (version 2.5.4a, May 2, 1995), also developed by the USDA Forest Service. In addition to providing the user with header information (airspeed, altitude, heading, etc.) from the AIRDAS data, it contained several user controlled options. Option one was the selection of roll correction.

Roll correction rectified the imagery to account for the roll of the aircraft during data collection. This option was always selected, even though roll inputs were inoperative during several collection periods. Option two required the selection of channels to be processed. Typical selection included all four AIRDAS channels even though channels one and two contained no usable data for this study. CREATE IMAGE transformed the BIP format data received from EXTRACT to band interleaved by line (BIL) format that could be imported to an image analysis program. The AIRDAS data was divided by eight to exclude the three low order bits which were only noise. The output pixels were signed 16 bit integers that ranged from -4095 to +4095.

The next step involved the use of a program called SCAN FIX, developed by the NASA Ames Ecosystems Science Branch. SCAN FIX geometrically corrects for image distortion caused by the AIRDAS scan angle, which induced variations in pixel size as the scan angle increases from nadir. SCAN FIX obtained 714 across-track pixels from AIRDAS data and transformed them into a maximum of 1050 across-track pixels. This process had the effect of producing pixels of all the same size relative to the ground area.

After the desired data had been extracted and corrected, the ERDAS IMAGINE, version 8.2, software package was used for image analysis. IMAGINE accepts generic binary, signed 16 bit formatted data.

C. DATA ANALYSIS

1. Strategy

The fireplace detection strategy was to use only the thermal imagery to determine whether or not the fireplace was operating,

then verify this with known fireplace usage information gathered by phone calls to volunteer participants.

The first step included positive identification of each control house on the aerial photographs and on the imagery collected during each flight. Then, using only AIRDAS imagery, determine if the fireplaces on the control houses were lit and compare this with the information obtained from the control house volunteers. Any discrepancies would be noted and investigators would attempt to explain them.

In attempting to explain discrepancies, investigators would assume that information received from the volunteers was correct. Volunteer information was only questioned if they were not sure of the start and stop time of fireplace usage or if the start time was close to the data collection time.

2. Results

To achieve the best quality image possible from the data collected, various IMAGINE functions and tools aided in the manipulation of imagery from each flight. All AIRDAS imagery is represented in the figures with the beginning of a flight line shown at the top of the page, continuing along the flight line down the page.

Figure 5-1 shows imagery of study area 1, using AIRDAS channel 4 data, from the flight at 1700 hours on December 15, 1995. Actual data collection began at 1706, with the entire image requiring approximately 40 seconds to collect. The Learjet flew a southerly heading commencing at the northern boundary of area 1. In Figure 5-1, the northern boundary is located at the top of the image and the southern boundary at the bottom. The uneven edges of the

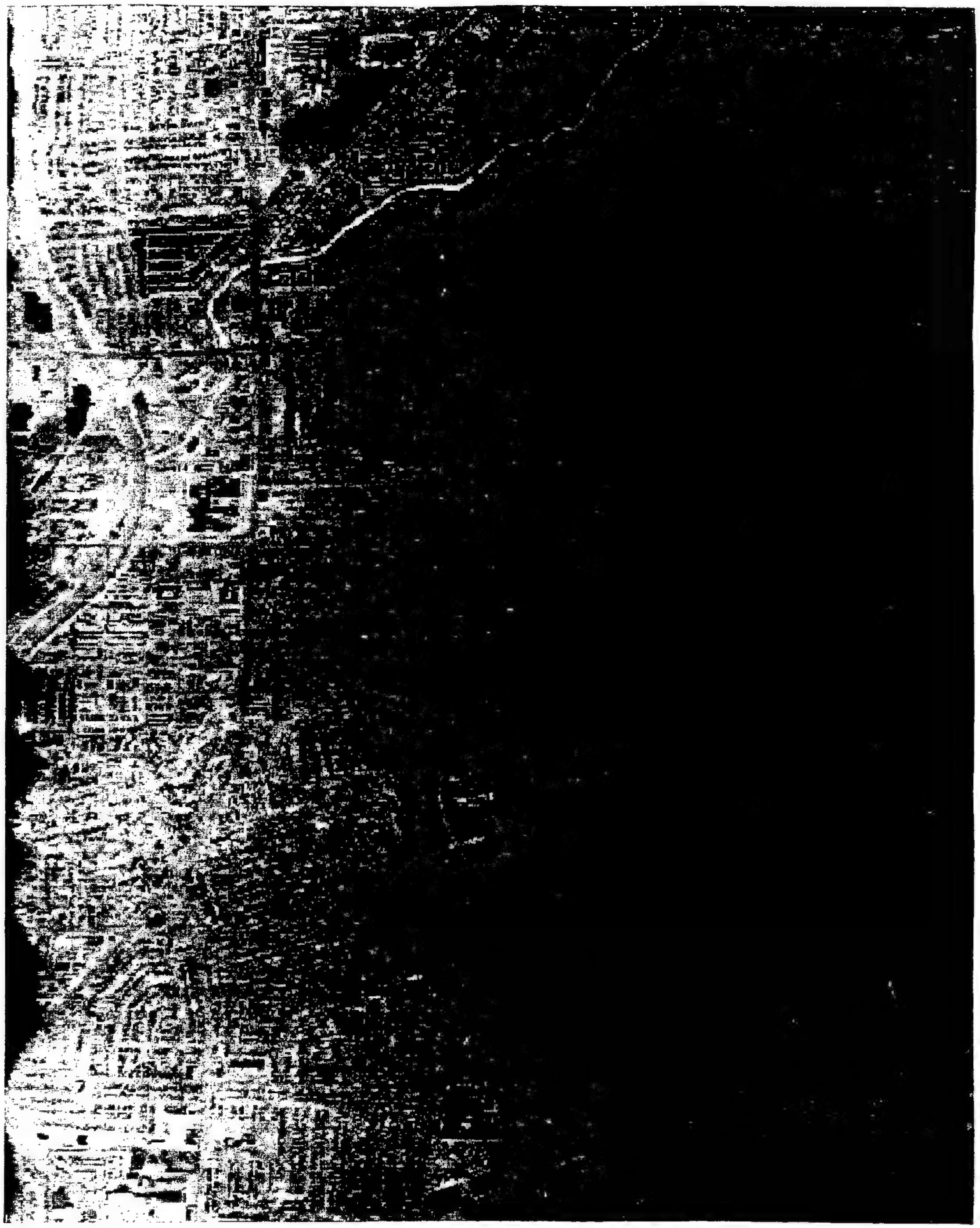

Figure 5-1. AIRDAS Channel 4 Thermal Imagery of Study Area 1 From 1700 Flight on December 15, 1995.

imagery were caused by the roll rectification applied to the data using the CREATE IMAGE roll correction option. Streets, roads and large buildings were easily discernible from this image as well as a creek that can be seen in the upper left hand corner of the image. The right and left edges of Figure 5-1 show how the quality of the image changed as AIRDAS scanned across track. Crisper, clearer imagery was obtained when the scanner was at nadir, gradually degrading in quality as the scan angle increased to the maximum FOV. The middle one third of the image, a swath approximately one mile wide, contains the area encompassed by study area 1, though some of the control houses were located outside of that boundary.

Figures 5-2 and 5-3 show AIRDAS channel 4 thermal imagery of study area 2 on December 15, 1995. Collection commenced at 1715 PST and finished three minutes and forty seconds later. Area 2 was divided into two images due to the size and upload time of the data file. Data collection initiated at the eastern end of the area, top of Figure 5-2, and continued to the western boundary, bottom of Figure 5-3. Roads, residential areas, and bodies of water were all easily discernible from the imagery.

Magnified portions of the imagery were used to identify specific control houses. As the magnification was increased, the surface characteristics were still discernible, down to individual houses, but much of the detail was lost as individual pixels became visible.

Figures 5-4 and 5-5 show representative examples of the magnified imagery used to determine the presence of lit fireplaces on control houses. Both images are from area 1 data collected on the 1900 flight, of December 15, 1995. The control house is in the

Figure 5-2. AIRDAS Channel 4 Thermal Imagery of the Eastern Portion of Study Area 2, Collected on December 15, 1995 at 1700.

Figure 5-3. AIRDAS Channel 4 Thermal Imagery of Western Portion of Area 2, Collected on 1700 Flight of December 15, 1995.

approximate center of each image and identified by an arrow. Figure 5-4 is an image of control house number three and Figure 5-5 shows control house number six. At the time of this imagery, both control houses had their fireplaces lit for nearly two hours. Control house number three lit their fireplace at 1730 and number six's was lit at 1645. (See Appendix C for fireplace and chimney information on each control house.)

At the level of magnification used in Figures 5-4 and 5-5, the boundaries of each house were jagged and not easily determined. This made detection of lit fireplaces difficult at best, since most of the control house fireplace chimneys were located at the edge of the roof lines. In the case of control house number three, the last condominium in a row of three, the chimney was located on the middle of the right-side wall of the building. Control house number six's chimney was located on the right-side rear portion of the roof. In each image, there was no single pixel that was readily identifiable as a lit fireplace chimney, even though volunteers at both houses had lit their fireplaces at least 1.5 hours prior to collection of imagery.

In the case of control house number three, a possible answer to the question of why a specific pixel could not be referenced to a lit fireplace chimney lies in the type of fireplace and fuel burned. This house had a natural gas fireplace and the amount of heat produced may not have been sufficient to raise the temperature of the chimney and therefore the radiance level of a pixel. But, this same explanation does not work with control house number six, whose participants burned wood in a brick fireplace.

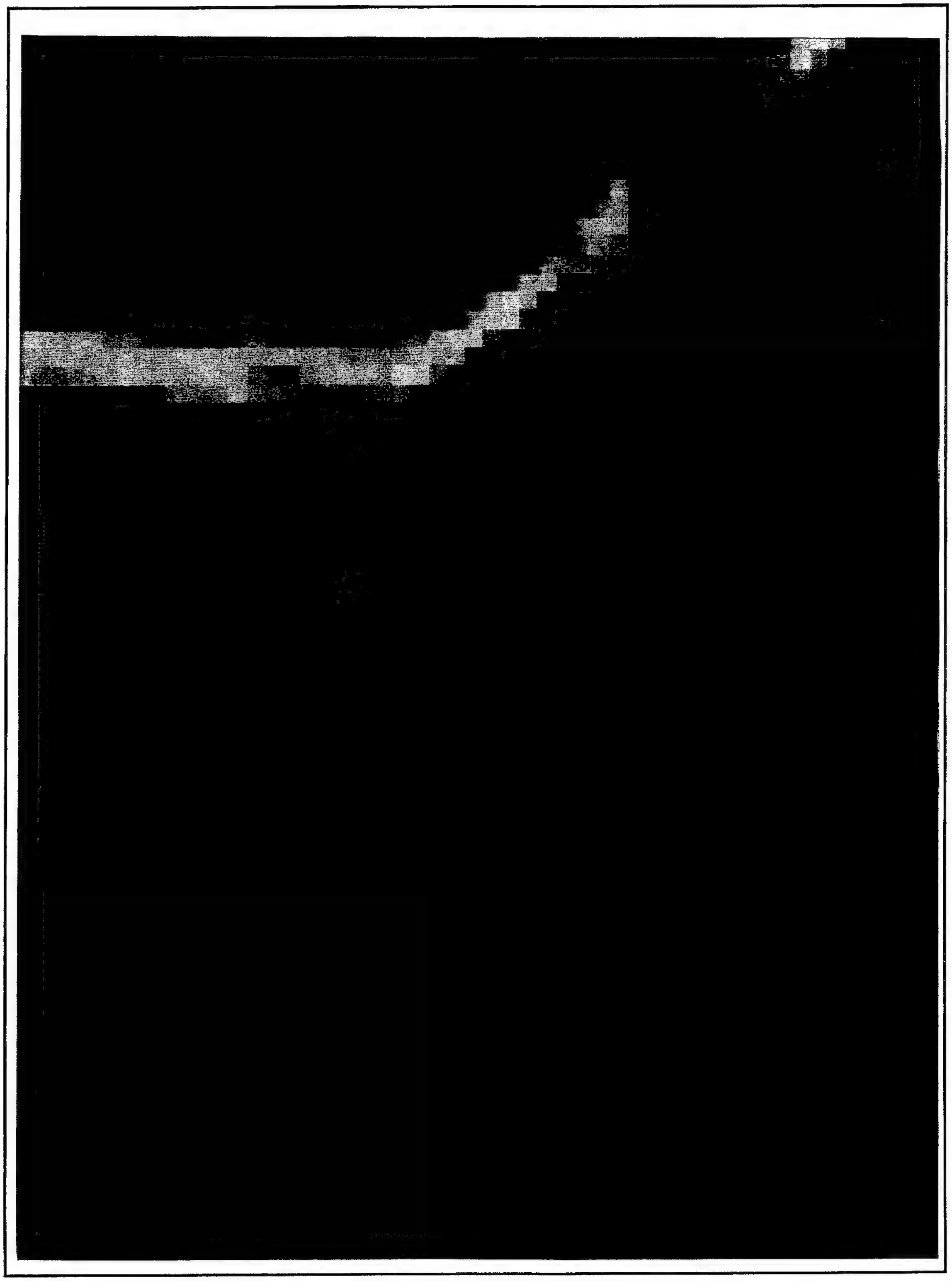

Figure 5-4. AIRDAS Channel 4 Thermal Imagery of Control House Three, Collected on 1900 Flight of December 15, 1995.

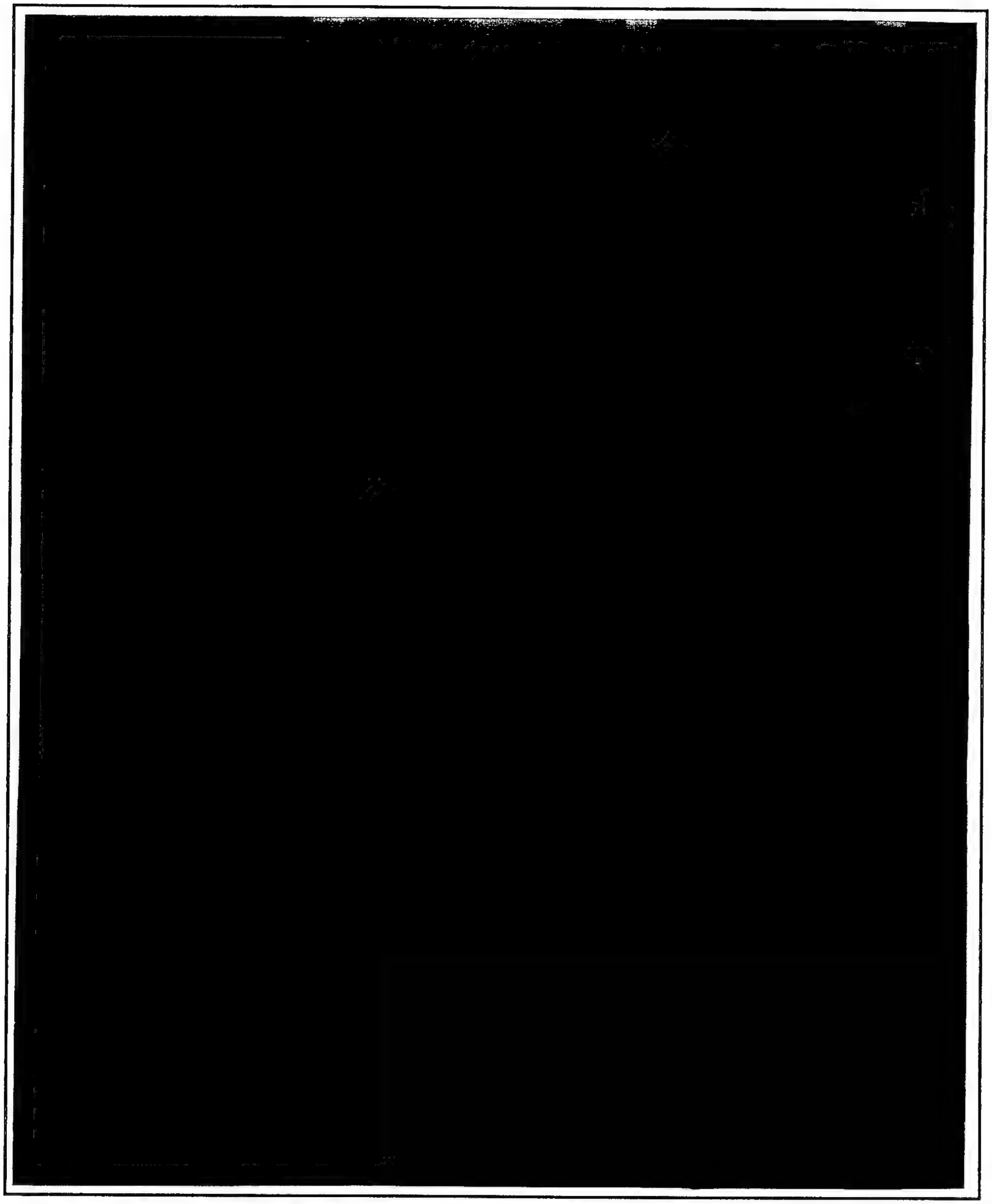

Figure 5-5. AIRDAS Channel 4 Thermal Imagery of Control House Six, Collected on 1900 Flight of December 15, 1995.

I performed the same imagery analysis for each control house visible in the imagery for each data collection flight. The best imagery was collected on December 15, 1995, during the flight at 1700 hours. Roll corrected imagery was not possible for the flight at 1900 hours on December 15, 1995, due to an inoperative roll gyro on AIRDAS. This imagery, though still useful, was difficult to analyze, due to the roll-induced distortion of the imagery. Figure 5-6 shows the non-roll-corrected imagery of study area 1 collected on December 15, at 1900. Comparing figure 5-1 to 5-6. The effect of roll correction on the quality of imagery is readily observable. Control houses were still identifiable in the imagery, though the overall effect was a reduction in the quality and usefulness of the imagery due to the resulting lack of detail and clarity.

The imagery from January 22 was dominated by dark pixels, producing a loss of detail, to the point that control houses could not be identified. Figure 5-7 shows imagery collected from the 1800 flight on January 22, 1996. The difference in quality between the December 15 imagery and the January 22 imagery is readily apparent when comparing Figure 5-1 and Figure 5-7. The quality of imagery from each subsequent flight on January 22 grew progressively worse.

Imagery generated using AIRDAS channel 3 data helped to retrieve some usable information from the January 22 data. Figure 5-8 shows the imagery of study area 1 produced using channel 3 data collected on January 22 during the flight at 1800 hours. Channel 3 data produced better quality imagery than channel 4, but the high level of noise prevented identification of control houses after image magnification. As with channel 4 imagery, the channel 3

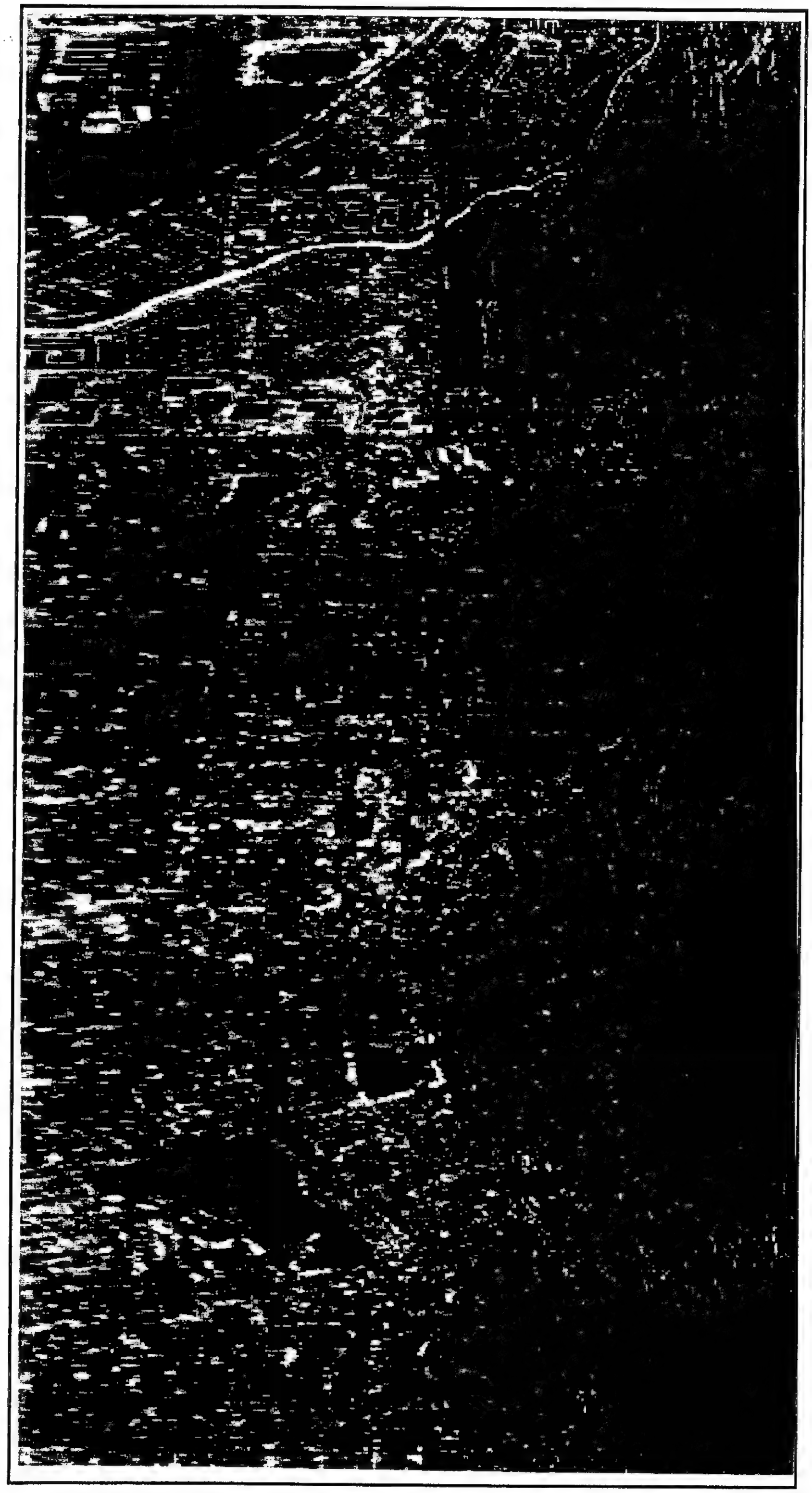

Figure 5-6. AIRDAS Channel 4 Imagery of Study Area 1 Without Roll Correction. Collected on 1900 Flight of December 15, 1995.

Figure 5-7. AIRDAS Channel 4 Thermal Imagery of Study Area 1, Collected January 22, 1996 at 1800.

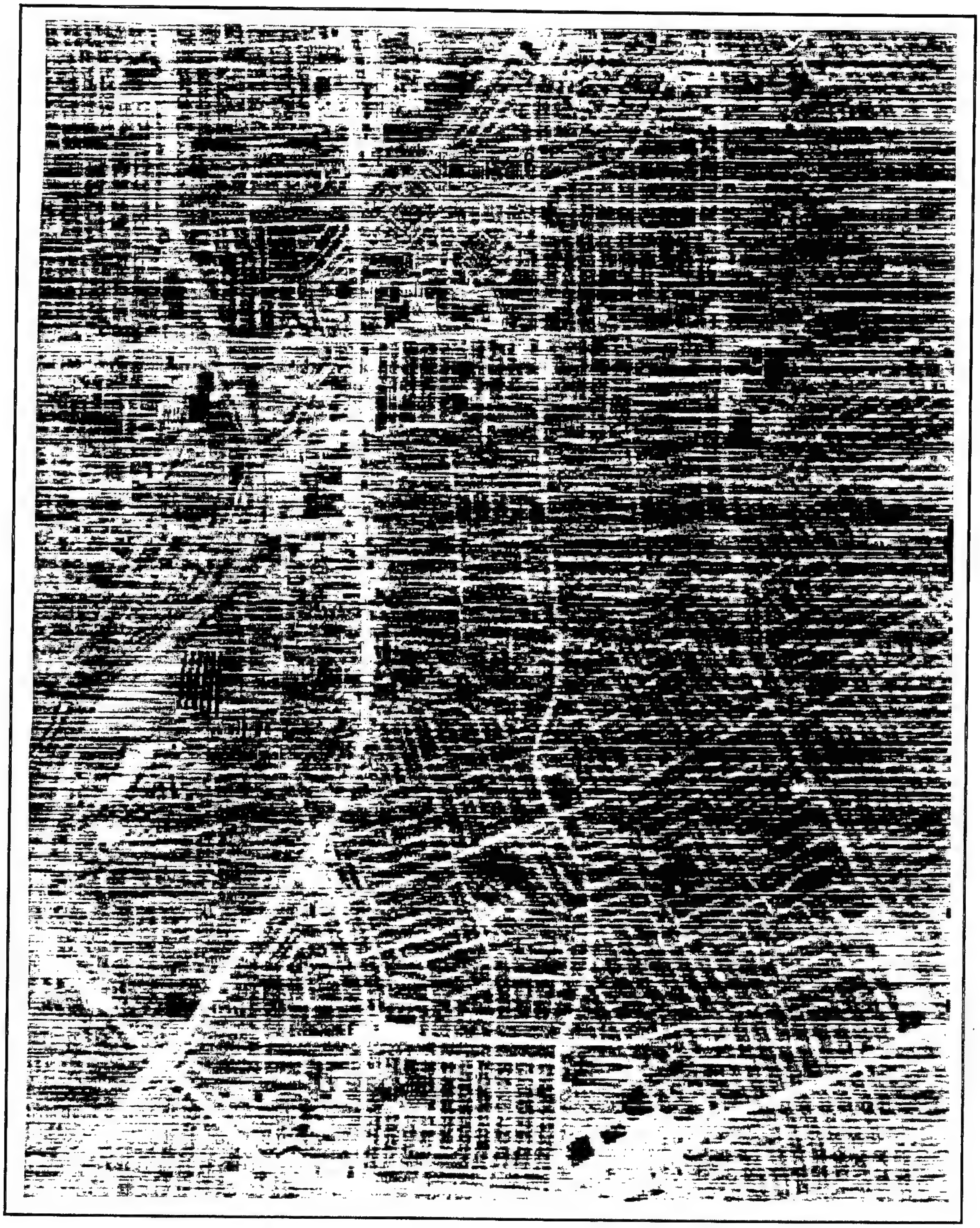

Figure 5-8. AIRDAS Channel 3 Imagery of Study Area 1. Collected January 22, 1996 at 1800.

image quality progressively degraded with each successive flight that night.

In an attempt to explain the differences in the quality of imagery collected during the December 15 and January 22 flights, I conducted an examination of key variables and parameters pertaining to imagery collection. All aircraft parameters, including altitude and airspeed remained constant relatively throughout both flights. AIRDAS system settings, including the blackbody reference temperatures, also remained constant. Weather was the only variable that differed between the two nights. Both nights were clear, but on the night of January 22, the ambient air temperature was as much as 15°F colder than it was on the night of December 15. During imagery analysis, discussions with the AIRDAS manager and system operator led me to believe that the reduction in temperature, coupled with the setting of the AIRDAS blackbody temperatures, combined to produce the results shown in Figure 5-7. Unfortunately, much of the corporate knowledge of the AIRDAS data collection process was lost, with the death of its designer, before a detailed operating manual could be created.

Results of the house-by-house analysis to detect lit fireplaces using AIRDAS thermal imagery are listed in Appendix F. In all cases, the results remained the same: no lit fireplaces could be positively identified using only thermal imagery.

I observed several other items of interest while analyzing the imagery for control houses three and six (see Figures 5-4 and 5-5). On both images, there appeared areas with the light gray and, in some cases, almost white pixels. In each case, comparison of the thermal imagery to the aerial photographs showed that these lighter shaded

pixels correspond to water. In Figure 5-4, the light line of pixels above the control house is small creek and Figure 5-5 shows a swimming pool in the backyard of the house located just above control house six.

Searching AIRDAS channel 4 thermal imagery for other "hot" pixels, produced several significant results. A single white pixel, located in study area one, was easily visible in slightly magnified imagery. Figure 5-9 shows the pixel in upper middle one-third of the imagery and Figure 5-10 shows that same area magnified several more times. Comparison of the imagery with the aerial photographs showed that the single white pixel was a hot tub located next to a pool house in an apartment complex. Though not measured, the hot tub appeared to be approximately 2 meters across (determined using cars and houses, visible in the aerial photographs, as size references).

The significance of readily identifying water and other large objects, such as houses and roads on the imagery, shows that AIRDAS has the temperature resolution necessary to differentiate between large objects with small temperature differences.

To confirm this observation, I obtained the corresponding digital numbers of a representative sample of pixels from the imagery. The digital numbers were compared to the results of an AIRDAS channel four low temperature calibration test to determine the temperature of the various objects. Imagery pixel digital numbers and the corresponding temperatures for various objects are given in Table 5-1.

Figure 5-9. AIRDAS Imagery of Study Area 1
From the 1700 Flight on December 1995.

Figure 5-10. Magnification of Imagery Displayed in Figure 5-9, Showing the Single White Pixel Associated with a Hot Tub.

Object of interest	Pixel digital number	Temperature of object (°C)
house roof	-2313	13.5
house roof	-2277	13.5
house roof	-2302	13.5
house roof	-2268	13.5
creek	-1771	18
creek	-1715	18
swimming pool	-1700	19
swimming pool	-1623	19
hot tub	-1204	22.5

Table 5-1. Pixel Digital Number and Corresponding Temperature for Selected Objects.

Temperatures of the roofs, creeks and swimming pools derived from the thermal imagery were identical to what we would expect the actual temperatures of the objects to be during the collection flights. This conclusion is based on the ambient air temperature during imagery collection and measurements of lit fireplace chimney and roof temperatures (Appendix B).

Though easily identifiable on the imagery, the temperature difference between the specific objects studied was only 9°C (16°F). This shows that AIRDAS system has sufficient radiometric or temperature resolution to perform the required detection as demonstrated by the values in Table 5-1. This was an important point in determining that the limiting factor in AIRDAS's capability to detect lit fireplaces was size of the ground resolution cell.

To show the effect that a reduction in the size of the ground resolution had on the quality of the imagery, I conducted a comparison between AIRDAS and Radiance 1 IR camera imagery. Using Equation 4-1, given the IFOV of 1.52 milliradians and sensor height above ground of 5000 ft, the ground resolution cell was calculated as 2.3 m,

nearly half the size of the resolution delivered by AIRDAS. Figure 5-11 shows a portion of AIRDAS imagery over study area 2 and Figure 5-12 shows the same area as collected by Radiance 1. The quality of imagery collected by Radiance 1 is greatly improved compared to the same imagery collected by AIRDAS. Unfortunately, none of the imagery collected by Radiance 1 contained any of the control houses used in the study. Therefore, a confirmation that a decreased ground resolution cell would enable the detection of lit fireplaces was impossible.

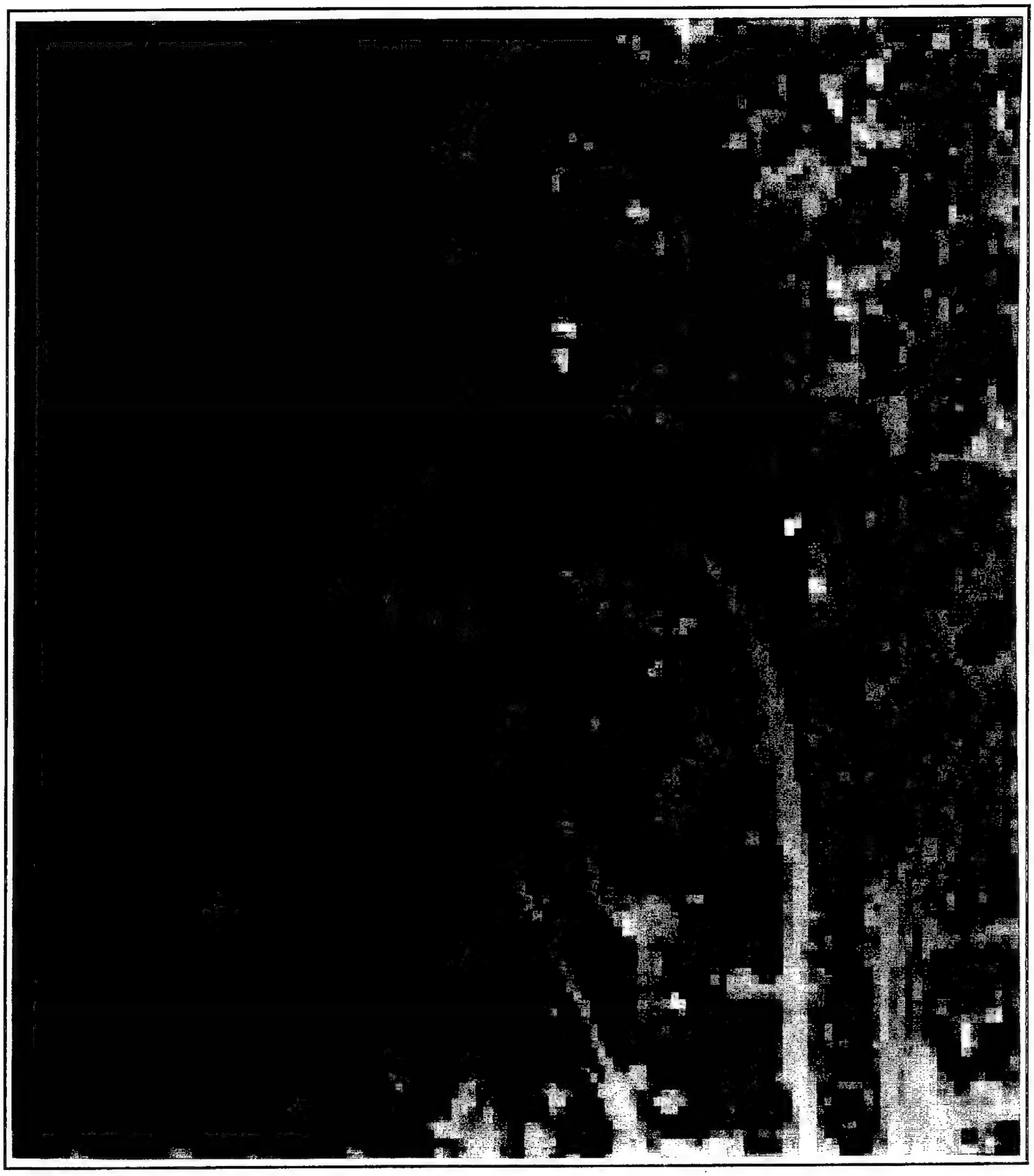

Figure 5-11. AIRDAS Imagery of a Portion of Study Area 2 From the 1700 Flight on December 15, 1995.

Figure 5-12. Radiance 1 imagery of the Same Portion of Study Area 2 as Shown in Figure 5-11. Collected December 15, 1995.

VI. CONCLUSIONS AND RECOMMENDATIONS

Comparison of results obtained through the analysis of AIRDAS imagery and fireplace usage information received from volunteers showed that the parameters and equipment used for this experiment were inadequate to detect lit fireplaces. Several possible reasons for this failure include:

- The temperature of a lit chimney was insufficient to raise the average temperature of the pixel, as measured by AIRDAS, to a level easily discernible on the thermal imagery, due to the size of the overall pixel.

- We worked at the low end of the AIRDAS channel four temperature range.

- Possible effect of the AIRDAS blackbody temperature settings on the output data used to construct the thermal imagery.

Solutions to these problems center around the size of the ground resolution cell and an unfamiliarity of the operators and managers as to how AIRDAS imagery is affected by changing parameters. Changing the size of the ground resolution cell will not only increase the detail of the imagery increase, but it will also cause smaller heat sources to raise the average temperature level of a pixel to a level that would make it easily discernible on the imagery. We can only obtain smaller ground resolution cells by changing the platform on which AIRDAS is flown or by upgrading the AIRDAS electronics to increase the scan rate available. By changing the AIRDAS platform to an aircraft capable of slower speeds, the ground resolution cell could be reduced by nearly one-third from that

of the four meters available on this experiment. A Piper Navajo flying at 120 kts and 3,500 feet would be able to obtain a ground resolution cell of 2.8 meters. An increase in the scan rate from 23 per second to 60-70 per second would also provide for a reduction in the size of the ground resolution cell. AIRDAS mounted on the Learjet, flying at the same airspeed, 180 kts, but with a scan rate of 60 per second, would provide a ground resolution cell of 1.6 meters. Both of these increases would provide dramatic improvements over the ground resolution cell available during the conduct of this experiment.

To increase the level of understanding of the AIRDAS system, I recommend that future users run multiple laboratory tests, changing only one parameter (i.e., blackbody temperatures, scan rate, ambient temperature, etc.) at a time, to determine the effect on the resulting imagery.

All participants in this experiment strongly felt that lit fireplace chimneys were detectable using the AIRDAS system if a sufficiently small ground resolution cell could be used and recommended that further testing be conducted in this area.

Spatial resolution was the limiting factor in my ability to detect lit fireplaces. I believe additional data collection, with a ground resolution cell of a maximum of 2 meters, will provide positive detection of lit fireplaces. This is based on a comparison of the imagery obtain by the AIRDAS system to that obtained by the Radiance 1 IR camera. Although AIRDAS imagery, with a ground resolution cell of 3.8 meters, showed much detail with houses and roads able to be differentiated, the actual boundaries and shapes of each were somewhat less discernible. But, in examining the Radiance 1 imagery, with a ground resolution cell of approximately

2.4 meters, the boundaries between different features are much more apparent. In addition, the actual shapes of the features (i.e., buildings and swimming pools) are readily seen in the Radiance 1 imagery. The ability to obtain a 2 meter ground resolution cell is well within the capabilities of the planned upgrades to the AIRDAS system.

Airborne particulate matter is an air quality issue that must be addressed, and the measurement of woodsmoke's contribution to this problem should be further examined.

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APPENDIX A

RESIDENTIAL FIREPLACE DENSITY MEASUREMENT USING AIRBORNE MULTI-SPECTRAL SENSORS

Test Plan

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OBJECTIVE

There are two objectives for this Director's Discretionary Fund (DDF) project. First, determine whether or not we can detect lit fireplaces well enough to count them or at least provide usable data to Bay Area Air Quality Management District (BAAQMD). Most everyone with multi-spectral imaging expertise agrees that this can be done, although no one has specifically looked for fireplaces.

The second objective is to find the most efficient way of determining lit fireplace density. Lit fireplaces should stand out on a thermal infrared

image. Although, other hot spots on the homes, such as hot water heater, furnace exhaust pipes, and efficient, low-emission wood-burning stoves may also be equally visible.

SCOPE

This test plan will serve as the basis for the airborne data collection, the ground based data collection and an overview of the Fireplace Density Measurement Project.

FIREPLACE DENSITY MEASUREMENT OVERVIEW

The San Francisco BAAQMD is looking for an efficient way of determining the approximate number and spatial distribution of fireplaces and wood stoves that are in use on a given night. This information would be used to help BAAQMD develop an inventory of emissions from residential wood burning and, ultimately, to evaluate the contribution of residential wood burning to ambient levels of particulate in the Bay Area.

The NASA-Ames Learjet will carry the Airborne Infrared Disaster Assessment System (AIRDAS) four channel scanner to conduct such a survey over a large portion of the Bay Area in just a few hours. These scanners detect the amount of thermal energy emitted from objects on the ground, relative to preset reference temperatures, thereby giving an indication of surface temperatures. The average surface temperature of a lit chimney on a cold winter night should be between 50 deg C and 80 deg C, versus a roof temperature of about 10 deg C.

The first step will be to take local radiometric temperature measurements of the surfaces of typical fireplace chimneys and wood burning stoves exhausts. This will help determine the proper temperature range settings for the airborne scanners.

The Learjet will fly three AIRDAS data acquisition lines at 5000 feet AGL over several residential neighborhoods on a night cold enough that many people would be using their fireplaces. We would then analyze the data at NASA Ames to see if we can differentiate lit fireplaces from other heat sources and count the number of houses with lit fireplaces. Its sensor actually indicates a single average reflected or emiited energy level for an entire ground resolution cell (i.e., it cannot distinguish between different objects within the same cell). Although the standard chimney is smaller than the ground resolution cell, the substantially higher temperature should be enough to saturate the cell with the emitted energy, making it standout from the surrounding cells. With an approximate 3.9 meter resolution, individual homes and streets should also be identifiable.

We will conduct a survey of the neighborhoods to find out which houses actually had fireplaces in use during the time of the flight and compare them with the houses identified in the imagery.

GROUND SURVEY

In order to verify the remotely sensed data, ground surveys will be conducted in conjunction with data collection fights. The local areas to be tested during the flights are Campbell, Los Gatos and Redwood City. The ground survey data of the Campbell and Los Gatos areas will be

obtained by requesting volunteer homeowner participation through the Ames Center Director Bulletin, Ames Astrogram and a NASA press release. Volunteers will be asked to give their telephone number, address and information about their fireplace usage. Names are optional and addresses will be kept confidential. NASA Ames point of contact for volunteer participants is Virginia Hays, the Medium Altitude Branch secretary. Researchers will contact volunteer households on the day before or on the day of the test to confirm participation and gather information on intended fireplace usage. Researchers would again contact participating households within a few days after the test to verify the fireplace use information. Questionnaires have been developed to ensure required information is obtained. This information will include start/stop time of fireplace usage, type of fuel burned (wood or gas), type of fireplace in use and whether or not they have spark arrestors installed.

In the Redwood City test area Dr. Wayne Ott is conducting an ongoing survey of 120 houses. Part of his survey data collection includes whether or not a house has a lit fireplace. On the evening of the data collection flights, we will request that he gather information on fireplace usage for the 120 houses in his survey area. He will collect data at 2 hour intervals, beginning at 1800 and ending at 0200.

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(415) 364-1430

GROUND TEST

A ground based test will be conducted to determine representative chimney surface temperatures of lit fireplaces. This data is important in order to properly set the temperature range that the AIRDAS will scan. This ground survey will be conducted on the weekend prior to the data collection flights. The Raytek ST4L portable, handheld, infrared thermometer will be used to take measurements. It measures the radiometric surface temperature of an object. Surface temperatures will be taken on several fireplace types using different fuel types.

FLIGHT TESTS

Flights will originate from NASA Ames Research Center on board the NASA Ames Learjet (N705NA). There will be five flights in the course of the evening. Each flight will last approximately 30 minutes and cover three predetermined lines. The pre-flight brief will be at 1630 in the operations room in building N211, with the first takeoff at 1800 (+/- 1/2 hour). Additional flights will occur at two hour intervals; takeoff times will be 2000, 2200, 2400 and 0200 (+/- 1/2 hour).

Test flights will be weather dependent. We will require cold and clear conditions in order to ensure optimal sensor employment.

AIRDAS temperature range and sensitivity settings will be determined from ground based temperature measurements.

FLIGHT PROFILE

Altitude: 5500 feet

ground speed: 180 knots or less

Flight #1 1800

Line #1: (Campbell Area)

Course: 180 deg

Endpoints: N 37 deg 19.00 min, W 121 deg 55.35 min
N 37 deg 15.00 min, W 121 deg 55.35 min

Line #2: (Los Gatos Area)

Course: 270 deg

Endpoints: N 37 deg 14.60 min, W 121 deg 52.50 min
N 37 deg 14.60 min, W 122 deg 00.00 min

Line #3: (Redwood City Area)

Course: 310 deg (parallel El Camino Real)

Endpoints: N 37 deg 27.10 min, W 122 deg 12.50 min

N 37 deg 28.25 min, W 122 deg 14.25 min

Successive flights will be made over the same lines at 2000, 2200, 2400 and 0200 (takeoff times +/- 1/2 hour).

GROUND SUPPORT

Ames badging for advisors (entire flight week).

Phil Martien

Bay Area Air Quality Managment District

Medium Altitude Branch approval for the following Learjet passengers:

Jeff Jenner, NASA

LCDR Pete Stoll, USN

Phil Martien, BAAQMD

Dr. Dave Cleary, NPS

FLIGHT SUPPORT/FLIGHT EQUIPMENT

The primary instrument will be the Airborne Infrared Disaster Assessment System (AIRDAS). AIRDAS is a four channel scanner designed to collect digital information in four spectral bands of the electro-magnetic spectrum. The AIRDAS data is collected on Exabyte 8mm data storage tapes from a 8500 device. The AIRDAS is composed of the scan-head and equipment rack.

AIRDAS operation and data collection will be conducted by Bob Higgins. Airspeed, position and time shall be recorded at the beginning and end of each data acquisition line.

Require seating for one AIRDAS operator and two observers.

DATA DISPOSITION

Two copies of each Exabyte tape will be delivered to LCDR Pete Stoll, who will coordinate the data reduction.

SCHEDULE

(1995)

December 6	Equipment checkout and route familialization flight
December 8	Data collection flights (weather permitting)
December 9	Back-up flight date

(1996)

March 22	Paper submission for Second International Airborne Remote Sensing Conference
May	Final Report to NASA Ames Center Director
June 24-27	Paper presentation at the Second International Airborne Remote Sensing Conference and Exhibition, San Francisco

REFERENCE DOCUMENT

Residential Fireplace Density Measurement Using Airborne Multi-spectral Sensors (NASA Ames Director's Discretionary Fund Proposal, March 17, 1995).

Pete Stoll Residential Fireplace Density Test Plan 12/5/95
(408) 656-3755

APPENDIX B

GROUND TESTS OF FIREPLACE CHIMNEY TEMPERATURE MEASUREMENT USING HANDHELD MINI INFRARED THERMOMETER.

Abbreviations: FP = Fireplace
OAT = Outside Air Temperature

Test #1
Date: 01 December 1995
Location: 14300 N. Alpine Road, Lodi, California
Fireplace Type: brick interior with red brick exterior
Chimney: ??
Wood: cherry
Roof: wood shingles, tar coated
Start time: 1530
Last Log Added: 1900
Weather: overcast, calm wind (rain and light wind from 1700 - 1800)
Sensor Emissivity Setting: 0.95

Time	FP Rear Wall (°C)	Chimney Side (°C)	Roof 3' from FP (°C)	OAT (°C)	Remarks
1530	19	20	21	20	
1630	18	19	20	19	
1700	18	20	20	19	light rain (sprinkle) light variable wind
1730					interior fireplace brick face 30-50°C
1900	16	18	15	18	
1945	16	19	15		
0000	16	19	13	14	rain; ground and roof wet

Table B-1. 14300 N Alpine Rd Chimney Temperature Measurements.

Test #2
Date: 01 December 1995
Location: 14170 N. Alpine Road, Lodi, California
Fireplace Type: insert with red brick exterior
Chimney: ??
Wood: walnut and pine
Roof: tar shingles
Start: 2000
Last Log Added: ??
Weather: overcast, calm wind (rain and light wind from 1700 - 1800)
Sensor Emissivity Setting: 0.95

Time	FP Rear Wall (°C)	Chimney Side (°C)	Roof 3' from FP (°C)	OAT (°C)	Remarks
1900	28	21	16	18	
1930	29	23	15		
0000	30	23	13	14	rain; ground and roof wet

Table B-2. 14170 N. Alpine Rd Chimney Temperature Measurements.

Test #3
Date: 02 December 1995
Location: 1515 Kahler Court, San Jose, California
Fireplace Type: insert with sheet metal flue (wood and plaster exterior)
Chimney: 1' diameter metal cover over flue; 3' square metal cover over chimney box
Wood: pine
Roof: clay tile
Start: 2000
Last Log Added: 2100
Weather: clear and calm
Sensor Emissivity Setting: 0.95

Time	Chimney Side (°C)	Roof 3' from FP (°C)	Flue Cover (°C)	Chimney Cover (°C)	OAT (°C)	Remarks
2000	6	2			≈10	gas hot water heater vent 1' from side of chimney: 18-20°C
2100	9	1	68	30-45		-roof had heat effected zone within 3' of chimney side: increase of ≈1°C per foot -sensor pointed directly into flue gas: 90°C
2300	7	0	21	10	4	

Table B-3. 1515 Kahler Ct Chimney Temperature Measurements.

APPENDIX C

CONTROL HOUSE FIREPLACE AND CHIMNEY INFORMATION

Chimney placement described from a position of looking at the control house from the street and noting the chimney position based on the following table:

Back of House

Left Aft	Center Aft	Right Aft
Left Middle	Center Middle	Right Middle
Left Front	Center Front	Right Front

Front of House

Table C-1. Control House Chimney Placement.

Control House #	Type of Fireplace	Type of Fuel	Chimney Placement (see Table D-1)
1	brick	Duraflame log	center front
2	brick	wood	left aft
3		natural gas	right middle
4	brick	wood	center middle
5	brick	wood	right front
6		hardwood	right aft
7		natural gas	
8	wood stove insert	wood	left middle
9	brick	scrap wood & pine	center aft
10		wood	right front

Table C-2. Study Area #1 Control House Information.

Control House #	Type of Fireplace	Type of Fuel	Chimney Placement
11	Flugo Heatalator	wood - oak	left middle
12	brick	wood	right & left middle
13		wood	left middle
14	brick	wood	center aft
15	brick	wood	right middle
16	Buckstone insert	wood - dry oak	right middle
17	catalytic converter	wood	right aft
18	"Little Buck" insert	wood - oak	unable to place
19			center front
20	brick	wood - pine	unable to place
21	brick	wood - oak	center aft
22	brick	wood	center aft
23	brick	Duraflame	left aft
24	Heatalator	wood	center aft
25		wood	right & left middle
26		wood	center middle
27	wood stove	wood	left aft
28			center aft
29		wood	center middle
30		wood	center front
31		natural gas	left front, right mid.
32	EPA stage 2 insert	wood - oak	center aft
33	Franklin woodstove	wood	right aft
34		wood	left front & right aft
34	brick	wood	center middle

Table C-3. Study Area #2 Control House Information.

APPENDIX D

METEOROLOGICAL DATA

This appendix contains meteorological data for a specified period of time collected from the Meteorological Tower Network operated by the San Francisco Bay Area Air Quality Management District. The data are presented in the following format:

ID	M	D	YY	H	WS	WD	T	RH
5905	2	24	90	12	6.9	40	72.0	37
5905	2	24	90	16	-99.9	-99	-99.9	-99
5905	2	24	90	17	4.1	290	56.4	76

where

ID	Site Identification Number (See below)
M	Month
D	Day
YY	Year
H	Hour (Pacific Standard Time)
WS	Wind Speed (MPH)
WD	Wind Direction (degrees from true north)
T	Temperature (°F)
RH	Relative Humidity (%)

A value equal to -99 or -99.9 indicates either missing or excluded data. All times are hour-beginning (i.e., HOUR 0 represents 12AM - 1AM PST.)

Site ID	Name	Latitude (deg)	Longitude (deg)	Elevation (meters above sea level)
7905	Alviso	37.352 N	121.952 W	1.0
5905	Ft Funston	37.715 N	122.500 W	57.0
6901	San Carlos	37.512 N	122.251 W	1.0
7902	S.J. Airport	37.355 N	121.927 W	17.0
6801	San Mateo Sewage	37.570 N	122.294 W	3.0
5801	San Francisco Sewage	37.741 N	122.390 W	5.0

ID	M	D	YY	H	WS	WD	T	RH
7905	12	15	95	0	8.3	166	54.8	-99
7905	12	15	95	1	8.8	156	54.7	-99
7905	12	15	95	2	9.2	140	54.6	-99
7905	12	15	95	3	10.9	139	54.5	-99
7905	12	15	95	4	9.2	147	54.4	-99
7905	12	15	95	5	8.2	135	53.5	-99
7905	12	15	95	6	7.7	149	53.9	-99
7905	12	15	95	7	5.4	164	53.6	-99
7905	12	15	95	8	5.9	153	53.4	-99
7905	12	15	95	9	4.3	165	53.3	-99
7905	12	15	95	10	3.8	150	54.8	-99
7905	12	15	95	11	3.2	150	56.8	-99
7905	12	15	95	12	4.8	325	57.5	-99
7905	12	15	95	13	10.7	311	59.1	-99
7905	12	15	95	14	12.0	306	58.9	-99
7905	12	15	95	15	13.0	310	58.0	-99
7905	12	15	95	16	2.6	301	55.2	-99
7905	12	15	95	17	11.8	302	53.7	-99
7905	12	15	95	18	9.9	288	52.6	-99
7905	12	15	95	19	9.2	285	51.5	-99
7905	12	15	95	20	7.5	284	50.9	-99
7905	12	15	95	21	6.0	321	51.5	-99
7905	12	15	95	22	4.3	22	49.6	-99
7905	12	15	95	23	2.3	327	48.8	-99
5905	12	15	95	0	16.4	193	58.2	92
5905	12	15	95	1	15.0	186	58.4	90
5905	12	15	95	2	16.1	181	58.8	88
5905	12	15	95	3	22.2	203	58.0	92
5905	12	15	95	4	13.6	197	55.2	94
5905	12	15	95	5	16.2	204	55.7	93
5905	12	15	95	6	13.5	200	55.6	94
5905	12	15	95	7	15.5	197	55.3	96
5905	12	15	95	8	13.0	225	55.1	96
5905	12	15	95	9	6.8	267	55.2	92
5905	12	15	95	10	7.0	254	56.4	92
5905	12	15	95	11	8.9	257	57.2	90
5905	12	15	95	12	8.8	272	57.5	89
5905	12	15	95	13	10.1	277	57.4	87
5905	12	15	95	14	13.0	290	57.1	83
5905	12	15	95	15	15.3	292	56.5	82
5905	12	15	95	16	13.7	309	55.7	80
5905	12	15	95	17	14.4	312	54.8	79
5905	12	15	95	18	11.2	322	54.2	77
5905	12	15	95	19	10.1	304	53.8	81
5905	12	15	95	20	11.8	317	53.7	80
5905	12	15	95	21	11.4	317	52.9	78
5905	12	15	95	22	13.5	321	53.0	75
5905	12	15	95	23	13.1	329	52.8	75

ID	M	D	YY	H	WS	WD	T	RH
6901	12	15	95	0	8.1	156	59.5	71
6901	12	15	95	1	8.0	141	59.2	72
6901	12	15	95	2	10.9	134	58.7	73
6901	12	15	95	3	11.0	150	58.1	74
6901	12	15	95	4	9.3	199	55.1	84
6901	12	15	95	5	5.9	141	54.8	84
6901	12	15	95	6	7.1	149	54.5	88
6901	12	15	95	7	5.2	161	54.3	89
6901	12	15	95	8	3.9	136	54.3	90
6901	12	15	95	9	3.9	157	55.0	88
6901	12	15	95	10	4.1	263	59.5	74
6901	12	15	95	11	10.8	302	61.2	66
6901	12	15	95	12	11.9	301	62.2	58
6901	12	15	95	13	14.3	298	60.4	60
6901	12	15	95	14	12.5	291	60.1	60
6901	12	15	95	15	13.8	300	57.7	64
6901	12	15	95	16	10.6	294	55.8	68
6901	12	15	95	17	12.4	291	53.9	71
6901	12	15	95	18	11.3	290	53.1	70
6901	12	15	95	19	7.1	285	52.4	73
6901	12	15	95	20	8.1	290	51.6	75
6901	12	15	95	21	10.8	296	51.5	72
6901	12	15	95	22	8.0	304	50.7	74
6901	12	15	95	23	8.6	310	50.2	72
7902	12	15	95	0	6.7	164	53.6	71
7902	12	15	95	1	5.8	153	53.9	71
7902	12	15	95	2	7.2	149	52.4	74
7902	12	15	95	3	7.9	137	51.5	77
7902	12	15	95	4	5.0	149	50.8	82
7902	12	15	95	5	6.1	117	49.6	93
7902	12	15	95	6	6.0	140	50.1	93
7902	12	15	95	7	5.8	144	51.1	93
7902	12	15	95	8	5.8	129	51.4	95
7902	12	15	95	9	2.6	201	51.4	97
7902	12	15	95	10	2.2	157	52.4	94
7902	12	15	95	11	3.6	156	54.7	87
7902	12	15	95	12	3.5	166	56.5	81
7902	12	15	95	13	2.8	274	55.9	80
7902	12	15	95	14	6.3	285	57.7	67
7902	12	15	95	15	8.5	297	57.7	63
7902	12	15	95	16	7.7	290	55.7	67
7902	12	15	95	17	5.5	289	52.2	76
7902	12	15	95	18	4.7	271	50.3	80
7902	12	15	95	19	5.1	278	49.3	80
7902	12	15	95	20	3.9	277	48.0	82
7902	12	15	95	21	5.5	300	49.1	81
7902	12	15	95	22	4.8	292	49.0	81
7902	12	15	95	23	5.1	300	48.3	80

ID	M	D	YY	H	WD	WS	T	RH
6801	12	15	95	0	4.8	189	58.9	73
6801	12	15	95	1	4.8	170	58.9	73
6801	12	15	95	2	7.1	140	58.4	74
6801	12	15	95	3	8.8	174	57.9	77
6801	12	15	95	4	6.0	157	54.2	87
6801	12	15	95	5	5.2	141	54.6	88
6801	12	15	95	6	4.3	142	54.7	88
6801	12	15	95	7	1.9	199	54.5	90
6801	12	15	95	8	4.0	199	54.6	90
6801	12	15	95	9	4.1	251	55.5	86
6801	12	15	95	10	4.9	315	57.9	76
6801	12	15	95	11	8.1	318	58.6	74
6801	12	15	95	12	10.9	285	59.0	65
6801	12	15	95	13	11.4	282	58.5	64
6801	12	15	95	14	12.2	299	58.4	63
6801	12	15	95	15	13.1	292	57.3	65
6801	12	15	95	16	10.3	288	55.4	69
6801	12	15	95	17	10.6	289	54.4	69
6801	12	15	95	18	12.3	287	53.7	70
6801	12	15	95	19	9.6	286	53.0	73
6801	12	15	95	20	7.6	288	52.8	74
6801	12	15	95	21	7.6	293	52.4	71
6801	12	15	95	22	8.7	301	51.7	71
6801	12	15	95	23	6.1	291	51.3	69
5801	12	15	95	0	9.8	186	59.1	82
5801	12	15	95	1	11.8	180	59.0	82
5801	12	15	95	2	12.4	173	58.5	84
5801	12	15	95	3	13.3	203	58.3	85
5801	12	15	95	4	8.1	225	55.6	86
5801	12	15	95	5	8.2	209	56.3	82
5801	12	15	95	6	5.6	194	55.3	88
5801	12	15	95	7	7.6	207	55.2	91
5801	12	15	95	8	7.7	234	55.8	89
5801	12	15	95	9	5.7	281	55.9	85
5801	12	15	95	10	8.9	286	57.2	82
5801	12	15	95	11	10.2	284	57.8	77
5801	12	15	95	12	12.7	282	58.1	72
5801	12	15	95	13	14.5	282	58.1	69
5801	12	15	95	14	13.8	293	57.4	71
5801	12	15	95	15	12.3	285	56.8	71
5801	12	15	95	16	12.0	292	55.8	71
5801	12	15	95	17	6.7	285	54.9	68
5801	12	15	95	18	6.5	270	54.2	66
5801	12	15	95	19	10.8	292	53.7	69
5801	12	15	95	20	10.2	308	53.3	71
5801	12	15	95	21	7.9	319	52.9	68
5801	12	15	95	22	6.7	343	52.6	68
5801	12	15	95	23	8.5	344	52.4	66

ID	M	D	YY	H	WS	WD	T	RH
7905	1	22	96	0	4.0	162	45.2	-99
7905	1	22	96	1	7.0	271	45.7	-99
7905	1	22	96	2	7.6	320	46.0	-99
7905	1	22	96	3	12.8	335	45.0	-99
7905	1	22	96	4	12.5	331	44.6	-99
7905	1	22	96	5	12.2	339	43.5	-99
7905	1	22	96	6	12.2	341	42.7	-99
7905	1	22	96	7	10.8	328	42.3	-99
7905	1	22	96	8	12.3	336	43.2	-99
7905	1	22	96	9	9.4	340	44.9	-99
7905	1	22	96	10	11.9	329	47.4	-99
7905	1	22	96	11	11.2	316	49.2	-99
7905	1	22	96	12	10.3	320	50.5	-99
7905	1	22	96	13	11.3	314	51.6	-99
7905	1	22	96	14	11.2	307	52.4	-99
7905	1	22	96	15	11.4	306	52.0	-99
7905	1	22	96	16	10.9	299	51.1	-99
7905	1	22	96	17	10.7	299	49.5	-99
7905	1	22	96	18	9.2	281	47.7	-99
7905	1	22	96	19	6.0	272	45.6	-99
7905	1	22	96	20	4.6	258	44.2	-99
7905	1	22	96	21	3.2	116	43.8	-99
7905	1	22	96	22	4.8	131	42.7	-99
7905	1	22	96	23	4.5	139	41.7	-99
5905	1	22	96	0	12.9	323	47.8	75
5905	1	22	96	1	15.7	326	46.7	73
5905	1	22	96	2	16.4	326	46.3	70
5905	1	22	96	3	14.4	332	46.3	67
5905	1	22	96	4	15.1	332	46.2	66
5905	1	22	96	5	15.8	331	46.3	65
5905	1	22	96	6	13.0	324	46.1	64
5905	1	22	96	7	13.8	328	46.0	63
5905	1	22	96	8	14.7	329	46.8	60
5905	1	22	96	9	12.6	327	48.0	57
5905	1	22	96	10	10.6	328	50.0	55
5905	1	22	96	11	12.7	322	51.3	55
5905	1	22	96	12	15.0	308	51.7	59
5905	1	22	96	13	16.5	307	52.0	63
5905	1	22	96	14	18.7	307	52.1	64
5905	1	22	96	15	19.1	309	52.0	66
5905	1	22	96	16	17.7	314	51.5	68
5905	1	22	96	17	12.2	322	50.5	69
5905	1	22	96	18	7.8	334	49.3	68
5905	1	22	96	19	11.1	325	49.2	68
5905	1	22	96	20	11.3	319	49.2	70
5905	1	22	96	21	8.1	331	48.7	68
5905	1	22	96	22	6.5	337	48.2	70
5905	1	22	96	23	4.0	31	46.9	73

ID	M	D	YY	H	WS	WD	T	RH
6901	1	22	96	0	7.7	281	45.0	80
6901	1	22	96	1	5.1	275	44.4	76
6901	1	22	96	2	7.4	293	43.9	71
6901	1	22	96	3	7.9	299	43.4	68
6901	1	22	96	4	8.1	298	42.9	63
6901	1	22	96	5	5.7	278	43.2	60
6901	1	22	96	6	5.5	283	42.9	64
6901	1	22	96	7	2.9	287	42.5	63
6901	1	22	96	8	6.0	289	44.7	60
6901	1	22	96	9	8.2	321	47.6	49
6901	1	22	96	10	7.1	330	49.8	47
6901	1	22	96	11	7.9	343	51.7	43
6901	1	22	96	12	5.7	9	52.4	45
6901	1	22	96	13	6.8	349	53.6	43
6901	1	22	96	14	7.9	334	53.1	46
6901	1	22	96	15	13.0	294	54.3	47
6901	1	22	96	16	13.5	290	52.6	52
6901	1	22	96	17	11.0	290	49.5	60
6901	1	22	96	18	8.7	289	47.9	63
6901	1	22	96	19	6.5	291	47.0	64
6901	1	22	96	20	5.9	288	46.2	65
6901	1	22	96	21	2.8	289	46.0	67
6901	1	22	96	22	3.0	258	45.4	71
6901	1	22	96	23	5.4	280	44.5	71
7902	1	22	96	0	2.2	173	43.2	94
7902	1	22	96	1	2.4	218	42.7	95
7902	1	22	96	2	6.0	268	41.6	92
7902	1	22	96	3	5.8	284	42.7	84
7902	1	22	96	4	5.0	288	42.5	80
7902	1	22	96	5	4.4	292	41.4	78
7902	1	22	96	6	3.7	310	39.8	78
7902	1	22	96	7	7.2	319	41.0	72
7902	1	22	96	8	7.5	326	42.8	69
7902	1	22	96	9	9.0	330	45.5	63
7902	1	22	96	10	8.7	325	47.5	59
7902	1	22	96	11	9.1	330	48.2	52
7902	1	22	96	12	8.0	328	49.5	46
7902	1	22	96	13	10.0	332	52.1	38
7902	1	22	96	14	9.6	330	52.6	40
7902	1	22	96	15	8.9	329	52.0	46
7902	1	22	96	16	8.2	312	51.6	49
7902	1	22	96	17	6.5	295	49.6	56
7902	1	22	96	18	5.5	268	45.9	69
7902	1	22	96	19	4.5	265	43.3	75
7902	1	22	96	20	2.3	232	41.4	78
7902	1	22	96	21	2.5	154	40.5	79
7902	1	22	96	22	2.6	160	38.8	82
7902	1	22	96	23	2.7	155	37.8	84

ID	M	D	YY	H	WS	WD	T	RH
6801	1	22	96	0	-99.9	-99	-99.9	-99
6801	1	22	96	1	-99.9	-99	-99.9	-99
6801	1	22	96	2	-99.9	-99	-99.9	-99
6801	1	22	96	3	-99.9	-99	-99.9	-99
6801	1	22	96	4	-99.9	-99	-99.9	-99
6801	1	22	96	5	-99.9	-99	-99.9	-99
6801	1	22	96	6	-99.9	-99	-99.9	-99
6801	1	22	96	7	-99.9	-99	-99.9	-99
6801	1	22	96	8	-99.9	-99	-99.9	-99
6801	1	22	96	9	-99.9	-99	-99.9	-99
6801	1	22	96	10	-99.9	-99	-99.9	-99
6801	1	22	96	11	-99.9	-99	-99.9	-99
6801	1	22	96	12	-99.9	-99	-99.9	-99
6801	1	22	96	13	-99.9	-99	-99.9	-99
6801	1	22	96	14	-99.9	-99	-99.9	-99
6801	1	22	96	15	-99.9	-99	-99.9	-99
6801	1	22	96	16	-99.9	-99	-99.9	-99
6801	1	22	96	17	-99.9	-99	-99.9	-99
6801	1	22	96	18	-99.9	-99	-99.9	-99
6801	1	22	96	19	-99.9	-99	-99.9	-99
6801	1	22	96	20	-99.9	-99	-99.9	-99
6801	1	22	96	21	-99.9	-99	-99.9	-99
6801	1	22	96	22	-99.9	-99	-99.9	-99
6801	1	22	96	23	-99.9	-99	-99.9	-99
5801	1	22	96	0	-99.9	-99	-99.9	-99
5801	1	22	96	1	-99.9	-99	-99.9	-99
5801	1	22	96	2	-99.9	-99	-99.9	-99
5801	1	22	96	3	-99.9	-99	-99.9	-99
5801	1	22	96	4	-99.9	-99	-99.9	-99
5801	1	22	96	5	-99.9	-99	-99.9	-99
5801	1	22	96	6	-99.9	-99	-99.9	-99
5801	1	22	96	7	-99.9	-99	-99.9	-99
5801	1	22	96	8	-99.9	-99	-99.9	-99
5801	1	22	96	9	-99.9	-99	-99.9	-99
5801	1	22	96	10	-99.9	-99	-99.9	-99
5801	1	22	96	11	-99.9	-99	-99.9	-99
5801	1	22	96	12	-99.9	-99	-99.9	-99
5801	1	22	96	13	-99.9	-99	-99.9	-99
5801	1	22	96	14	-99.9	-99	-99.9	-99
5801	1	22	96	15	-99.9	-99	-99.9	-99
5801	1	22	96	16	-99.9	-99	-99.9	-99
5801	1	22	96	17	-99.9	-99	-99.9	-99
5801	1	22	96	18	-99.9	-99	-99.9	-99
5801	1	22	96	19	-99.9	-99	-99.9	-99
5801	1	22	96	20	-99.9	-99	-99.9	-99
5801	1	22	96	21	-99.9	-99	-99.9	-99
5801	1	22	96	22	-99.9	-99	-99.9	-99
5801	1	22	96	23	-99.9	-99	-99.9	-99

ID	M	D	YY	H	WS	WD	T	RH
7905	1	23	96	0	3.1	160	41.0	-99
7905	1	23	96	1	4.6	148	40.6	-99
7905	1	23	96	2	5.3	139	39.5	-99
7905	1	23	96	3	5.9	152	38.9	-99
7905	1	23	96	4	6.6	148	39.1	-99
7905	1	23	96	5	6.3	157	39.5	-99
7905	1	23	96	6	7.6	148	40.4	-99
7905	1	23	96	7	8.3	152	41.5	-99
7905	1	23	96	8	8.4	155	43.7	-99
7905	1	23	96	9	7.3	145	45.9	-99
7905	1	23	96	10	8.6	145	46.6	-99
7905	1	23	96	11	9.2	153	48.9	-99
7905	1	23	96	12	10.5	156	50.8	-99
7905	1	23	96	13	9.5	154	52.8	-99
7905	1	23	96	14	8.9	151	53.5	-99
7905	1	23	96	15	8.3	157	53.1	-99
7905	1	23	96	16	8.4	155	52.8	-99
7905	1	23	96	17	8.7	159	51.4	-99
7905	1	23	96	18	7.9	162	51.1	-99
7905	1	23	96	19	6.4	143	50.4	-99
7905	1	23	96	20	5.6	148	49.9	-99
7905	1	23	96	21	6.5	144	49.9	-99
7905	1	23	96	22	6.4	146	49.8	-99
7905	1	23	96	23	6.3	156	49.7	-99
5905	1	23	96	0	2.7	75	46.4	73
5905	1	23	96	1	4.1	329	46.8	74
5905	1	23	96	2	2.3	86	45.5	76
5905	1	23	96	3	3.6	150	47.2	72
5905	1	23	96	4	6.1	131	45.7	74
5905	1	23	96	5	8.1	134	46.7	74
5905	1	23	96	6	8.0	168	48.1	80
5905	1	23	96	7	13.2	206	49.6	89
5905	1	23	96	8	14.9	191	49.2	93
5905	1	23	96	9	17.1	193	50.1	91
5905	1	23	96	10	16.3	191	51.3	89
5905	1	23	96	11	14.6	193	51.3	92
5905	1	23	96	12	15.5	194	51.8	92
5905	1	23	96	13	17.6	198	51.7	94
5905	1	23	96	14	17.0	202	51.7	94
5905	1	23	96	15	16.9	204	51.5	96
5905	1	23	96	16	16.1	198	51.4	96
5905	1	23	96	17	15.8	198	51.4	98
5905	1	23	96	18	14.9	195	51.7	97
5905	1	23	96	19	11.4	189	51.7	97
5905	1	23	96	20	9.8	188	52.1	95
5905	1	23	96	21	9.3	187	52.5	94
5905	1	23	96	22	13.5	206	53.2	96
5905	1	23	96	23	10.1	216	53.8	97

ID	M	D	YY	H	WS	WD	T	RH
6901	1	23	96	0	3.0	259	44.1	71
6901	1	23	96	1	1.8	179	41.8	76
6901	1	23	96	2	1.9	176	40.7	79
6901	1	23	96	3	2.4	163	40.4	80
6901	1	23	96	4	5.1	134	38.9	81
6901	1	23	96	5	4.1	165	39.3	79
6901	1	23	96	6	4.1	133	40.1	81
6901	1	23	96	7	4.1	130	41.4	77
6901	1	23	96	8	3.1	148	43.7	73
6901	1	23	96	9	3.2	106	46.5	75
6901	1	23	96	10	7.5	174	51.1	75
6901	1	23	96	11	6.9	146	53.1	72
6901	1	23	96	12	7.9	182	54.9	69
6901	1	23	96	13	7.7	212	56.8	66
6901	1	23	96	14	9.6	237	56.4	66
6901	1	23	96	15	7.4	230	56.0	68
6901	1	23	96	16	7.3	208	55.0	69
6901	1	23	96	17	6.4	213	54.2	70
6901	1	23	96	18	5.4	210	52.8	78
6901	1	23	96	19	3.9	167	51.1	86
6901	1	23	96	20	5.8	130	50.4	88
6901	1	23	96	21	5.7	135	49.9	86
6901	1	23	96	22	5.0	142	49.9	87
6901	1	23	96	23	2.8	127	49.5	92
7902	1	23	96	0	2.0	175	36.6	85
7902	1	23	96	1	3.4	149	36.2	87
7902	1	23	96	2	2.7	169	35.9	88
7902	1	23	96	3	3.5	163	35.7	90
7902	1	23	96	4	3.8	160	35.9	90
7902	1	23	96	5	4.2	162	36.8	88
7902	1	23	96	6	4.6	164	37.5	85
7902	1	23	96	7	6.6	143	39.6	80
7902	1	23	96	8	6.7	151	42.3	74
7902	1	23	96	9	7.4	148	44.8	70
7902	1	23	96	10	7.8	140	45.7	68
7902	1	23	96	11	8.0	147	47.8	67
7902	1	23	96	12	7.5	141	49.6	66
7902	1	23	96	13	7.7	140	52.5	64
7902	1	23	96	14	7.5	158	53.5	65
7902	1	23	96	15	6.8	165	53.1	68
7902	1	23	96	16	5.8	158	52.7	72
7902	1	23	96	17	4.8	167	51.9	74
7902	1	23	96	18	4.5	161	50.0	80
7902	1	23	96	19	4.9	137	48.8	86
7902	1	23	96	20	5.0	140	48.0	90
7902	1	23	96	21	5.3	143	47.8	92
7902	1	23	96	22	5.6	146	48.1	91
7902	1	23	96	23	4.8	155	48.1	91

ID	M	D	YY	H	WS	WD	T	RH
6801	1	23	96	0	-99.9	-99	-99.9	-99
6801	1	23	96	1	-99.9	-99	-99.9	-99
6801	1	23	96	2	-99.9	-99	-99.9	-99
6801	1	23	96	3	-99.9	-99	-99.9	-99
6801	1	23	96	4	-99.9	-99	-99.9	-99
6801	1	23	96	5	-99.9	-99	-99.9	-99
6801	1	23	96	6	-99.9	-99	-99.9	-99
6801	1	23	96	7	-99.9	-99	-99.9	-99
6801	1	23	96	8	-99.9	-99	-99.9	-99
6801	1	23	96	9	-99.9	-99	-99.9	-99
6801	1	23	96	10	-99.9	-99	-99.9	-99
6801	1	23	96	11	-99.9	-99	-99.9	-99
6801	1	23	96	12	-99.9	-99	-99.9	-99
6801	1	23	96	13	-99.9	-99	-99.9	-99
6801	1	23	96	14	-99.9	-99	-99.9	-99
6801	1	23	96	15	-99.9	-99	-99.9	-99
6801	1	23	96	16	-99.9	-99	-99.9	-99
6801	1	23	96	17	-99.9	-99	-99.9	-99
6801	1	23	96	18	-99.9	-99	-99.9	-99
6801	1	23	96	19	-99.9	-99	-99.9	-99
6801	1	23	96	20	-99.9	-99	-99.9	-99
6801	1	23	96	21	-99.9	-99	-99.9	-99
6801	1	23	96	22	-99.9	-99	-99.9	-99
6801	1	23	96	23	-99.9	-99	-99.9	-99
5801	1	23	96	0	-99.9	-99	-99.9	-99
5801	1	23	96	1	-99.9	-99	-99.9	-99
5801	1	23	96	2	-99.9	-99	-99.9	-99
5801	1	23	96	3	-99.9	-99	-99.9	-99
5801	1	23	96	4	-99.9	-99	-99.9	-99
5801	1	23	96	5	-99.9	-99	-99.9	-99
5801	1	23	96	6	-99.9	-99	-99.9	-99
5801	1	23	96	7	-99.9	-99	-99.9	-99
5801	1	23	96	8	-99.9	-99	-99.9	-99
5801	1	23	96	9	-99.9	-99	-99.9	-99
5801	1	23	96	10	-99.9	-99	-99.9	-99
5801	1	23	96	11	-99.9	-99	-99.9	-99
5801	1	23	96	12	-99.9	-99	-99.9	-99
5801	1	23	96	13	-99.9	-99	-99.9	-99
5801	1	23	96	14	-99.9	-99	-99.9	-99
5801	1	23	96	15	-99.9	-99	-99.9	-99
5801	1	23	96	16	-99.9	-99	-99.9	-99
5801	1	23	96	17	-99.9	-99	-99.9	-99
5801	1	23	96	18	-99.9	-99	-99.9	-99
5801	1	23	96	19	-99.9	-99	-99.9	-99
5801	1	23	96	20	-99.9	-99	-99.9	-99
5801	1	23	96	21	-99.9	-99	-99.9	-99
5801	1	23	96	22	-99.9	-99	-99.9	-99
5801	1	23	96	23	-99.9	-99	-99.9	-99

APPENDIX E

CONTROL HOUSE LIT FIREPLACE DETECTION USING THERMAL IMAGERY AND VOLUNTEER INFORMATION ON FIREPLACE USAGE.

Control house #	Digital line position of control house X	Y	Fireplace detection from image	Fireplace usage (PST)	Remarks
1	208	3154		1700-2000	poor image, near edge of scan
2				1500-late	house outside of scan
3	448	3298	no	1730-2315	good image
4	366	3525	no	1700-1930	
5	303	3646	no	1628-2130	
6	630	3754	no	1645-2000	
7	534	4119	no	1810-0000	good image
8	223	4216		1655-1940	poor image, near edge of scan
9				1645-2100	house outside scan
10				not lit	house outside scan

Table E-1. Imagery Analysis of Study Area 1.
December 15, 1995, 1706 PST Flight Data.

Control house #	Digital line position of control house X	Y	Fireplace detection from image	Fireplace usage (PST)	Remarks
1				1700-2000	house outside scan
2				1500-late	house outside scan
3	298		possible	1730-2315	
4	161		no	1700-1930	
5	28		possible	1628-2130	
6	452		no	1645-2000	good image
7	389		no	1810-0000	
8				1655-1940	house outside scan
9				1645-2100	house outside scan
10				not lit	house outside scan

Table E-2. Imagery Analysis of Study Area 1.
December 15, 1995, 1907 PST Flight Data.

Control house #	Digital line position of control house X	Y	Fireplace detection from image	Fireplace usage (PST)	Remarks
1				?	
2				1915-2230	
3				no	
4				1830-2000	
5				?	
6				1800-2015	
7				?	
8				1730-2230	FP lit prior to 1730
9				1830-2130	
10				1730-2130	

Figure E-3. Fireplace Usage Only of Study Area 1.
January 22, 1996

Control house #	Digital line position of control house X	Y	Fireplace detection from image	Fireplace usage (PST)	Remarks
11	913	8253	no	1200-2230	poor image, near edge of scan
12	802	8182	no	1645-2000	good image
13				1718-1800	house outside scan
14	287	8753	no	1930-2130	
15	714	8691	no	1700-2100	good image
16	412	9255	no	1630-1900	
17	535	9248	no	1630-1930	
18	341	9425	no	1630-1800	good image
19	135	9649	possible	1905-2230	poor image
20	407	9715	no	1845-2200	
21	283	9848	no	0930-?	
22	542	9914	no	1700-2100	
23	177	10073	no	unsure	poor image
24	202	10214	no	1300-2055	poor image
25	157	10198	no	no	
26	446	10413	no	no	
27	239	10543	no	1900-?	
28	588	10647	no	no	
29				1724-1942	house outside scan
30	210	11095	no	1800-2015	poor image
31	73	11626	no	no	poor image, near edge of scan
32				1600-2200	house outside scan
33				1730-2330	house outside scan
34				1600-1715	house outside scan
35				1720-1830	house outside scan

Table E-4. Imagery Analysis of Study Area 2.
December 15, 1995, 1715 PST Flight Data.

Control house #	Digital line position of control house X	Y	Fireplace detection from image	Fireplace usage (PST)	Remarks
11				1200-2230	house outside scan
12	796	1891	no	1645-2000	
13				1718-1800	
14	258	12459	no	1930-2130	
15				1700-2100	
16	387	12954	possible	1630-1900	
17	508	12942	possible	1630-1930	
18	354	13123	no	1630-1800	good image
19	153	13352	no	1905-2230	poor image
20	424	13405	no	1845-2200	
21	312	13542	no	0930-?	good image
22	572	13599	no	1700-2100	
23	221	13745	no	unsure	
24	230	14136	no	1300-2055	
25	205	14097	no	no	
26	476	14315	no	no	
27	258	14438	no	1900-?	
28	402	14401	no	no	
29				1724-1942	obscured by cloud
30	228	14979	no	1800-2015	poor image
31				no	unable to ID house
32				1600-2200	house outside scan
33				1730-2330	house outside scan
34				1600-1715	house outside scan
35				1720-1830	house outside scan

Table E-5. Imagery Analysis of Study Area 2.
December 15, 1995, 1916 PST Flight Data.

Control house #	Digital line position of control house X	Y	Fireplace detection from image	Fireplace usage (PST)	Remarks
11				1730-?	FP lit prior to 1730
12				2010-2300	
13				1830-2230	
14				1840-2015	
15				1800-2200	
16				1800-2000	
17				1730-2200	FP lit prior to 1730
18				1730-1855	FP lit prior to 1730
19				?	
20				1900-2100	
21				1730-2300	FP lit prior to 1730
22				1800-2110	
23				no	
24				1745-2100	
25				no	
26				yes	
27				1920-0000	
28				1825-0000	
29				1925-2100	
30				no	
31				no	
32				1800-2200	
33				1800-2130	
34				no	
35				1720-1945	

Table E-6. Fireplace Usage Information of Study Area 2. January 22, 1996.

APPENDIX F

AIRDAS CALIBRATION DATA

Calibration Temperature °C	Digital Number
60	2313
55	1985
50	1600
45	1198
40	836
35	467
30	73
25	-696
20	-1413
15	-2127
10	-2749
5	-3326
0	-3856
-5	-4096
-10	-4096

Table F-1. AIRDAS Channel 4 Calibration Data.

LIST OF REFERENCES

1. Fairley, David, and Robin De Mandel. *PM10 Particulate Levels in the Bay Area.* San Francisco, April 1992.

2. Jenner, Jeff. *Residential Fireplace Density Measurement Using Airborne Multi-Spectral Sensors.* FY96 Ames Director's Discretionary Fund Proposal. NASA Ames Research Center, March 1995.

3. Bay Area Air Quality Management District. *Measuring Air Quality - The Pollutant Standards Index.* San Francisco.

4. Martien, Phil. Personal interview. 22 August 1996.

5. Bay Area Air Quality Management District. *Woodburning Handbook.* San Francisco, 1992.

6. Ambrosia, Vincent G. *AIRDAS, Development of a Unique Four Channel Scanner for Natural Disaster Assessment.* Proc. of the First International Airborne Remote Sensing Conference. Strasbourg, France. September 1994.

7. Colwell, Robert N. *Manual of Remote Sensing, Volume 1.* 2nd ed. Falls Church: American Society of Photogrammetry, 1983.

8. Lillesand, Thomas M. and Ralph W. Kiefer. *Remote Sensing and Image Interpretation.* 3rd ed. New York: John Wiley & Sons, Inc., 1994.

9. Avery, Thomas, and Graydon Berlin. *Fundamentals of Remote Sensing and Airphoto Interpretation.* 5th ed. New York: Macmillan, 1992.

10. NASA Ames Research Center. *AIRDAS - Airborne Infrared Disaster Assessment System.* Fact Sheet. Moffett Field, CA.

11. Jenner, Jeffrey W. "Writing Test Plans." Naval Postgraduate School. Monterey, 07 Nov. 1995.

12. Jenner, Jeffrey W. *Residential Fireplace Density Measurement Using Airborne Multispectral Sensors.* FY96 NASA Ames Directors Discretionary Fund Proposal, March 1995.

13. NASA Ames Research Center. *NASA Lear Jet Airborne Observatory Aircraft Program.* Moffet Field CA., June 1993.

14. *Sunnyvale, California.* Map. San Francisco, CA: CSAA (AAA), February 1995.

15. *Central San Jose, California.* Map. San Francisco, CA: CSAA (AAA), September 1994.

16. *San Francisco VFR Terminal Area Chart.* Chart. Washington, D.C.: NOAA, October 1995.

17. *Los Gatos Quadrangle, California. 7.5 Minute Series (Topographic).* Map. Denver, CO: Department of the Interior, USGS, 1980.

18. *Palo Alto Quadrangle, California. 7.5 Minute Series (Topographic).* Map. Denver, CO: Department of the Interior, USGS, 1991.

19. *Castle Rock Ridge Quadrangle, California. 7.5 Minute Series (Topographic).* Map. Denver, CO: Department of the Interior, USGS, 1991.

20. *San Jose West Quadrangle, California. 7.5 Minute Series (Topographic).* Map. Denver, CO: Department of the Interior, USGS, 1980.

21. *San Jose East Quadrangle, California. 7.5 Minute Series (Topographic).* Map. Denver, CO: Department of the Interior, USGS, 1980.

22. *Santa Teresa Hills Quardrangle, California. 7.5 Minute Series (Topographic).* Map. Denver, CO: Department of the Interior, USGS, 1980.

23. Raytek. *ST4L Model Mini Handheld Thermal Infrared Thermometer.* Santa Cruz, CA. September 1995.

24. Jenner, Jeffrey W. "Use Your Fireplace In the Name of Research." *Nasa Ames Research Center Astrogram.* 17 November 1995: 8.

25. Mewhinney, Mike. *NASA News - NASA Researchers Seek Volunteers With Fireplaces.* NASA Ames Research Center Press Release. Mountain View, CA: November 21, 1995.

26. Rogers, Paul. "NASA Reveals a Burning Desire" *San Jose Mercury News.* November 1995: A1.

27. United States Geological Survey. *Directory of Contributors Western Region - Aerial Photography Summary Record System.* Menlo Park, CA: April 1994.

28. NASA Ames Research Center. *AIRDAS Mission Report A95-20-LD.* Mountain View, CA: December 1995.

29. NASA Ames Research Center. *AIRDAS Mission Report A95-21-LD.* Mountain View, CA: December 1995.

30. NASA Ames Research Center. *AIRDAS Mission Report A96-01-LD.* Mountain View, CA: January 1996.

31. NASA Ames Research Center. *AIRDAS Mission Report A96-02-LD.* Mountain View, CA: January 1996.

32. NASA Ames Research Center. *AIRDAS Mission Report A96-03-LD.* Mountain View, CA: January 1996.

33. NASA Ames Research Center. *AIRDAS Mission Report A96-04-LD.* Mountain View, CA: January 1996.

34. NASA Ames Research Center. *AIRDAS Mission Report A96-05-LD.* Mountain View, CA: January 1996.

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